Increasing understanding of complex biological concepts haptic learning in a collaborative, 3D environment

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Haptic Learning in a Collaborative, 3D Environment.

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Abstract

Cell biology is known to be a difficult subject due to its abstract and complex nature. Although concepts of cell biology are integral to the understanding of biology overall, misconceptions in cell biology have been identified across all levels of education. Haptic technology (which enables sensing and manipulating through touch) may offer a method of increasing understanding in complex, abstract and unobservable concepts such as those found in cell biology. The potential beneficial effects of haptics in learning complex biological concepts is supported by Dual Coding Theory (Paivio, 1969), Cognitive Load Theory (Sweller, 1994) and Embodied Cognition (Barsalou, 2008). The development and use of haptic systems in the medical field however has identified fine dexterity and spatial ability as factors that may influence the ability of students to interact with and learn from haptic systems (Shahriari-Rad, 2014). However, spatial ability and fine dexterity have not yet been examined in the use of haptics in the learning of complex biological concepts. This study used mixed methods research to determine whether haptic feedback has a beneficial effect on learning concepts of cell biology, whether fine dexterity or spatial ability has an impact on the ability of students to learn from haptic VR systems and discover which features of haptic interventions may support or not support learning in this topic.

A collaborative, 3D virtual reality (VR) learning environment capable of providing haptic feedback was developed allowing students to explore, interact and test hypotheses to further their understanding of cell biology. Sixty-four 12-13-year-old students were allocated to haptic (touch feedback enabled) and non-haptic (touch feedback disabled) conditions. Students worked in pairs to complete tasks designed to facilitate collaborative exploration of a 3D VR model of a cell membrane. This study was the first to compare haptic and non-haptic learning in science with a multi-fingered haptic device, which provided a more intuitive method of manipulation than previous haptic alternatives. Learning gains were measured using a test of cell knowledge administered before,

immediately after and 8 months after the activity to determine the effect of haptic feedback on learning. Fine dexterity and spatial ability were also measured to explore any effects of these variables in how students learned from the intervention. Thematic analysis of student interviews was also conducted to gain insight into which features of haptic interventions may support or not support students' learning in this topic.

It was found that students increased their knowledge significantly after the intervention and retained that knowledge for 8 months. Thematic analysis of the interviews identified several key themes suggesting that students enjoyed using the system and expressed a preference for interaction and collaboration in their learning. Students perceived increased understanding of the topic and predicted that they would retain their knowledge, which was consistent with the quantitative results. However, there were no significant differences in knowledge gain between haptic and non-haptic conditions. The thematic analysis identified possible sources of excess cognitive load and indicators of visual dominance which may have affected the influence of haptic feedback on learning in this study. Potential sources of excess extraneous cognitive load include the novelty of the system and difficulties grasping within the model, which have the potential to overload working memory and consequently negate beneficial effects provided by the haptic sense. Evidence for the effects of visual dominance were found, suggesting that the prominence of visual information is a detrimental factor in the use of haptic models. Spatial ability and 'tweezer' fine dexterity were not found to significantly affect how students learned from the intervention. However, it was found that those with lower 'finger' fine dexterity retained more of their knowledge in the long term. Finger fine dexterity is a factor which had not been previously explored in the use of haptic interventions for cell biology, but findings of this study indicate that further research is required to explore how dexterity may affect how students interact with models using multi-finger haptic systems.

This study is unique in its evaluation of a multi-fingered haptic device for the learning of cell biology and investigation into the effects of spatial ability and fine dexterity on how students learn from haptic systems in this topic. The findings of this study indicate that effects of extraneous cognitive load, visual dominance and fine dexterity must be addressed to determine optimal conditions for the use of haptic feedback in the learning of complex biological concepts.

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List of Abbreviations and Acronyms

Abbreviation	Full form
2D	2 Dimensional
3D	3 Dimensional
BDT	Block Design Test
CAP	Cognitive, Affective, and Psychomotor
CLT	Cognitive Load Theory
DCT	Dual Coding Theory
ICC	Intraclass correlation coefficient
KCL	King's College London
MMR	Mixed Methods Research
RQ1	Research Question 1
RQ2	Research Question 2
RQ3	Research Question 3
RQ4	Research Question 4
SRT	Spatial Relations Test
SUMI	Software Usability Measurement Inventory
SUS	System Usability Scale
NASA-TLX	The NASA Task Load Index
VR	Virtual Reality
WAIS-III	Wechsler Adult Intelligence Scale- Third Edition
WAMMI	Website Analysis and Measurement Inventory
WISC-IV	Wechsler Intelligence Scale for Children- Fourth Edition

1 Introduction

1.1 Introduction

This thesis presents a study on the effects of haptic feedback on the learning of abstract concepts within cell biology at secondary school level. As part of a research project in which this PhD resides, a 3D, virtual reality (VR) system was developed with the capability for haptic feedback provided by a multi-fingered haptic interaction device. This system was used to provide an exploratory learning environment which allowed students to work collaboratively, explore, test hypotheses, and learn about complex, abstract concepts. To determine the effects of haptic information on learning gains, the system was designed to be capable of delivering the same learning environment for all students with or without the presence of haptic feedback, allowing a comparison between students who experienced haptic feedback and those who did not. The role of spatial ability and fine dexterity in the ability for students to use and learn from the system are considered in this thesis. Additionally, students' perspectives are considered through interviews to determine features which may support or not support their learning.

This introductory chapter commences with an explanation of the context of this thesis in relation to the research project in which this PhD resides, followed by an overview of the background to the study, research aims and questions, research design and methodology and an overview of the structure of this thesis.

1.2 Context of this thesis

This PhD took place within a research project funded by the Leverhulme Trust. The research project involved several contributors from King's College London (KCL) (School of Education, Communication and Society), the University of Reading (Department of

Biomedical Engineering and Biological Sciences) and teaching staff from partner schools. The project team collaborated in design, development and testing throughout this research project with differing levels of involvement at varying points in the research. In this thesis therefore, it will be made clear who was responsible for each piece of work described, and whether that work was completed by myself, by another researcher in the project team, or completed collaboratively by the project group. In addition, a summary of the work I completed within this project alone and in collaboration with the project team can be seen in Appendix A.

This thesis has an educational focus and presents a study to determine the effects of haptic feedback on learning gains in cell biology, the effects of fine dexterity and spatial ability on students' ability to learn from a VR system capable of providing haptic feedback, and an exploration of student's perceptions on what supports or does not support their learning whilst using the haptic VR system. This thesis reports on previous literature, piloting and development of methodology, data analysis and findings, and discusses the findings of the study in relation to existing literature, underlying theory, and the context of the study in the wider research topic.

Further to the context of this thesis within the wider research project, the following section will summarise literature which provides contextual theoretical background to this thesis.

1.3 Background

Cell biology is abstract and complex in nature, presenting a challenge for educators to help students to successfully comprehend this topic and allow them to appreciate the complexity of cellular concepts (Bivall, Ainsworth, & Tibell, 2011). As a key topic in the understanding of biology as a whole (Verhoeff, Waarlo, & Boersma, 2008), but also a topic where many students fail to grasp fundamental ideas (Flores, Tovar, & Gallegos, 2003), methods of increasing understanding in cell biology have an important role in science education.

Difficulties in understanding cell biology are thought to be due to the need for the processing of abstract and cognitively demanding information. The importance of experimentation and physical hands-on experience in facilitating the learning of cognitively demanding information in science has been discussed in educational research (Zacharia, 2015), however, cell biology contains abstract and often intangible concepts which are not easily explored with physical experimentation. The development of technology with the potential to allow the manipulation and exploration of VR may offer a solution to the exploration and understanding of abstract micro-phenomena such as those found in cell biology. 'Haptic' technology uses 3D visual information and touch interfaces, allowing tactile feedback for exploration within a 3D space. The term 'haptic' has been used to refer to technology that enables a user to interact with VR, sensing and manipulating through touch (Kapoor, Arora, Kapoor, Jayachandran, & Tiwari, 2014; McLaughlin, Hespanha, & Sukhatme, 2002). This development of haptic technology makes possible the physical manipulation of previously inaccessible 3D, visual information.

Benefits of physical manipulation of abstract cellular concepts are supported by theories based on the 'modality principle' (Millar, 1999), which suggests that each sense has its own processing channel within the working memory. Relevant theories include Dual Coding Theory (DCT) (Paivio, 1969) and Cognitive Load Theory (CLT) (Sweller, 1994). DCT suggests that there are distinct systems for different sensory modalities that work together, allowing the beneficial effect of the combined coding of sensory information through separate processing channels. According to this theory, the addition of the haptic sense would work synergistically with other sensory modes to aid the coding of complex information, and is supported by evidence that in some cases the addition of the haptic sense has been shown to be beneficial for learning (M. S. Chan & Black, 2006). CLT

(Sweller, 1994) suggests that whilst learning, an individual's working memory is put under cognitive load as new information is attempted to be processed. Information is typically processed visually or auditorily, however, haptic devices provide sensory feedback in the form of touch, and it is thought that having a new channel for information in a different modality may help alleviate cognitive load and aid learning. CLT is supported by evidence that excess cognitive load can affect information processing (Skulmowski, Pradel, Kühnert, Brunnett, & Rey, 2016; Whelan, 2007). Another theory which supports the use of physical manipulation in learning is Embodied Cognition (Barsalou, 2008). Embodied Cognition suggests that multiple sensory modalities used during learning can integrate to create a multimodal representation stored in the memory, which can create cognitive anchors for understanding abstract concepts (Reiner, 2009). Therefore, according to Embodied Cognition, physical manipulation may utilise the haptic sense to allow multi-sensory representations stored in the memory to anchor abstract concepts. There is evidence for the embodiment of haptic information from studies looking at the impact of haptic manipulation on memory (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004; Ramani & Siegler, 2008).

Despite theoretical justification for the beneficial effects of haptic feedback in science learning, the literature is mixed (Minogue & Jones, 2006; Zacharia, 2015). It has been suggested that mixed results may be due to small sample sizes (Han, 2013), limited numbers of studies (Zacharia, 2015), and the effects of excess cognitive load (Minogue & Jones, 2006; Wiebe, Minogue, Jones, Cowley, & Krebs, 2009), which may have affected the ability of some studies to detect the beneficial effects of haptic feedback in learning. Additionally, some studies have cited the effects of visual dominance as a factor that may prevent studies from detecting the beneficial effects of haptic infomation. Visual dominance describes how, when presented with multiple modalities, the visual sense can dominate other senses (Posner, Nissen, & Klein, 1976), and some studies implicated visual dominance as a reason why their haptic activity may not have reached its full potential in enhancing learning (Minogue, Jones, Broadwell, & Oppewall, 2006; Wiebe et al., 2009).

Reviews of the use of haptics in science education concluded that there is evidence for the positive effect of haptic feedback in learning, but more research was needed. Additionally, abstract topics for which visual information is inadequate were identified as particularly suitable for the use of haptic feedback (Minogue & Jones, 2006; Zacharia, 2015). This criterion would correspond with concepts in cell biology (such as the concentration gradient across the cell membrane) which are difficult to convey visually and known to be difficult for students to understand (Dreyfus & Jungwirth, 1989; Flores et al., 2003).

The design of the haptic system and method of interaction could also affect whether haptic feedback is shown to be beneficial for learning. Two factors specified as relevant in this study were fine dexterity and spatial ability. Haptic devices for the manipulation of VR models come in many forms, such as joysticks, paddles, and tracker balls. Several studies have used the stylus-based ‘Phantom Touch 3D’ device, which provides higher sensitivity than previous devices. The Phantom uses a stylus to interact with the 3D virtual space and therefore necessitates the hand to rotate and navigate, requiring hand dexterity (Shahriari-Rad, 2014). For this study, a multi-fingered haptic device was developed, which allowed the user to navigate using their thumb and forefinger in a pinching motion, which involves similar fine dexterity to the Phantom device. Additionally, this study used a 3D cell membrane model viewed in VR for students to explore and navigate, which may implicate users’ existing spatial ability as a factor in how they interact and learn from the system. Therefore, existing fine dexterity and spatial ability may be of interest when using haptic VR systems such as the one used in this study.

Should haptic feedback be shown to be beneficial for learning in cell biology then this finding would contribute towards determining the usefulness of haptic technology in science education, and its potential to aid understanding in complex, key biological concepts. Additionally, should fine dexterity or spatial ability be implicated as significant factors in the use of a haptic VR system, then this finding could be influential in the design of systems in further research or may require further exploration to determine the extent of their relationship with haptic technology.

1.4 Research aims and questions

This study aims to determine whether haptic feedback has an effect on learning gains, and whether fine dexterity or spatial ability has an impact on the ability of students to learn from haptic VR devices. For these aims, a collaborative, 3D, VR learning environment capable of providing haptic feedback was developed which would allow students to explore, interact and test hypotheses to further their understanding of complex and abstract biological concepts concerning the cell membrane. This study also aims to explore which features of a haptic intervention for learning in science may support or not support students' learning, which may be revealed by looking in depth at students' perceptions of their experiences and learning through interviews.

To complete these research aims, the following research questions were developed:

1. Will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?
2. Does existing spatial ability have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?
3. Does existing fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?
4. What design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?

1.5 Research design and methods

To answer the research questions specified in Section 1.4, a pragmatic approach will be used. Pragmatism encourages the use of ‘whichever methods work’ for answering the research aims and questions (Tashakkori & Teddlie, 2010), which allows researchers to not be restrained to a particular research method or technique (Robson & McCartan, 2016) and allows the flexibility to utilise both quantitative and qualitative methods to improve the quality of the research (Onwuegbuzie & Leech, 2005).

Research Questions 1, 2 and 3 can be assessed quantitatively by comparing changes in knowledge test scores across time and by accounting statistically for existing fine dexterity and spatial ability scores. The fourth question, however, is more exploratory and thus, interviews are more appropriate to gather in-depth information on students’ perceptions. This study will therefore use mixed methods research (MMR), which allows the use of both qualitative and quantitative methods to provide better understanding than using either one in isolation (Creswell, 2011).

1.6 Thesis Structure

This thesis comprises six chapters, starting with this introductory chapter, which presents the context of the thesis in relation to the research project, a brief background to this study, research questions, methodology and the structure of the thesis.

Chapter 2 of this thesis contains a review of the literature. It begins with the literature concerning misconceptions in cell biology. The following sections within the literature review concern the role of spatial ability and visualisation in science education. Following this, the existing literature on haptic feedback in science education is discussed, including theories that suggest why haptic feedback may be helpful to learning such as Cognitive Load and Embodied Cognition theories.

Chapter 3 concerns the research methodology, design, and methods for this study. After presenting the research paradigms used in this study, each pilot study is reported and discussed in relation to the development of the main study method. Following this, the main study is documented, including the design, materials, participants, procedure, planned analysis and interviews.

Chapter 4 reports both the qualitative and quantitative data analysis conducted in this study. Firstly, the quantitative descriptive and inferential statistics are reported, followed by the thematic analysis of interviews .

Chapter 5 is a discussion of the findings of this study, beginning with the findings regarding Research Question 1, followed by Research Questions 2 and 3. The findings from the qualitative analysis are then discussed in relation to Research Question 4. Chapter 5

concludes this thesis by summarising the findings from this study and identifying contributions to the existing knowledge, implications of the findings, highlighting limitations of the study and recommendations for future research.

2 Literature Review

2.1 Difficulties in learning cell biology: misunderstandings and misconceptions

2.1.1 Introduction

Despite best efforts by educators, some students fail to grasp fundamental ideas in science classrooms (Flores et al., 2003). Some high achieving students may provide correct answers by memorising key information, but when questioned more carefully these students can reveal a failure to fully understand underlying concepts (Davis, 1997). It is generally agreed that students bring certain ideas with them to science lessons which are inconsistent with the ideas of teachers and scientists (Treagust, 1988), giving rise to misunderstandings (misinterpretation of facts) (Barrass, 1984) and misconceptions (preconceived, yet scientifically inaccurate ideas) (Bahar, 2003).

Misunderstandings and misconceptions may be especially prevalent in particularly complex and abstract topics. Cell biology, for example, is a complex but key topic in biological education (Verhoeff et al., 2008), for which the literature has shown several common misunderstandings and misconceptions spanning from primary to higher education (Dreyfus & Jungwirth, 1989; Flores et al., 2003; Tretter, Jones, Andre, Negishi, & Minogue, 2006; Vlaardingerbroek, Taylor, & Bale, 2014). This section will discuss the literature surrounding difficulties, misunderstandings and misconceptions in learning cell biology, recommendations for more effective learning according to the literature and how a haptic system may facilitate learning in this topic.

2.1.2 Difficulties in learning cell biology

Understanding cell biology has been said to be critical in the understanding of biology as a whole (Verhoeff et al., 2008). However, many students fail to acquire a coherent conceptual understanding of the cell as a basic unit of an organism. Dreyfus and Jungwirth (1988) demonstrated this with a diagnostic evaluation study examining to what extent 10th grade students had managed to internalise key ideas from their curriculum. Using questionnaires and in-depth interviews with 219 Israeli students, they found that that pupils considered the concept of the cell to be an abstract idea, giving rise to numerous misconceptions on the mechanism of the selective cell membrane, how the nucleus governs the cell, what cells have in common and what cells need energy for. For example, certain students believed that only liquid materials could pass through the membrane, that cells anthropomorphically ‘recognise’ materials which must penetrate and rejects others, takes in only molecules which it 'needs', digest proteins because they are ‘foreign bodies’, and that cells at rest do not need energy. Pupils also made incorrect conclusions in contradiction to correct knowledge they had previously shown, suggesting underlying conceptual misconceptions or misunderstandings. The authors went on to propose that when cellular processes can only be inferred from experiments in the classroom, pupils cannot observe cells functioning directly and therefore the cell remains an abstract concept open to misinterpretation (Dreyfus & Jungwirth, 1989).

Similar conclusions were drawn by a study by Flores et al. (2003), who investigated the conceptual problems of high school students with respect to the cell, its processes, structure and relation to the functions of multicellular organisms. Using questionnaire data from 1200 students on 8 different topics of cell biology, the authors found several problems with comprehension originating from previous ideas. Main topics of misunderstanding included the articulation between structural units, cells/multicellular organisms, functioning of the cell membrane, confusion between meiosis and mitosis, structural organisation, and recognising a variety of cell types. A persistent anthropomorphic view of processes and assigning of intentionality to cell function was also found, with students providing statements such as “cells know what they require, and take what they need from the environment", which is an issue documented previously in the literature (Bartov, 1978; Dreyfus & Jungwirth, 1988; Zohar & Tamir, 1993).

The literature therefore shows that the topic of cell biology is difficult for students to understand. The abstract, complex, and unobservable nature of cell biology means that misunderstandings and misconceptions concerning cellular concepts have been shown to be prevalent, including those concerning anthropomorphisation of the cell, functioning of the cell membrane, confusion between complex cellular processes such as respiration, photosynthesis, mitosis and meiosis and structural organisation. In addition to misunderstandings of cellular concepts, specific misconceptions have also been identified in the literature as a barrier to the effective learning of cell biology, which will be discussed in Section 2.1.2.1.

2.1.2.1 Misconceptions in cell biology

The literature has identified certain misconceptions which are common to the topic of cell biology acting as barriers to learning. This section will discuss prominent misconceptions in the topics of magnification and randomness (including osmosis and diffusion), which are discussed in the following sections.

2.1.2.1.1 Understanding Magnification

Difficulty comprehending size and scale has been described as a critical barrier to learning in science and higher level understanding (Hawkins, 1978; Swarat, Light, Park, & Drane, 2011). However, it has been shown that misunderstandings and misconceptions on the concept of size and scale regarding micro-phenomena (such as cells) span across levels of education. Tretter, Jones, Andre, Negishi, and Minogue (2006) explored conceptions of size and scale in elementary, middle, high school, and graduate students, finding that students were more accurate at understanding relative size than absolute size, and that direct (visual or kinaesthetic) or indirect experience is important to improving accuracy of size and scale. However, as cells are an abstract, unobservable phenomenon, direct experience with size and scale at the cellular level is difficult to obtain, which presents issues for the understanding of magnification in cell biology. Additionally, Tretter, Jones, and Minogue (2006) investigated the accuracy of spatial scale conceptions of 215 students from 5th , 7th , 9th and 12th grade, as well as doctoral level and found that accuracy on a large scale tended to decline smoothly as the scale increased, whereas accuracy on a small scale showed discontinuity at the microscopic level, suggesting a particular difficulty with understanding scale at the cellular level.

Additionally, Flores et al. (2003) found in their study that students often confuse atoms and molecules (e.g. stating that cells are similar in size to molecules and atoms), showing a misconception on the size and scale of parts of the cell. Harrison and Treagust (1996) also found in their study of mental models of atoms in high school students that students often confuse atoms and cells despite their difference in size (for example, suggesting that atoms are made up of cells). Regarding the comparison of very small sizes, Waldron, Spencer, and Batt (2006) found that many 11-13 year old students had difficulty correctly sizing germs, molecules and atoms relative to each other, suggesting that distinguishing between millimetres, micrometres and nanometres was a difficult task.

Problems understanding size and scale in nanoscale objects such as cells extends even to undergraduate level. Vlaardingerbroek et al. (2014) investigated first year university students' perceptions of cellular scale and size by asking 290 biology students what they expected to see under an optical microscope at a given magnification. Students were also asked to identify structures that would not be visible at the level of magnification, which was implied by an accompanying textbook diagram. The authors found that many students assumed that diagrams found in textbooks presented parts of cells in correct relative size, leading to widespread problems regarding scale and absolute size. Vlaardingerbroek et al. (2014) criticised diagrams in textbooks for showing all visible cellular characteristics at the level of magnification associated with optical microscopy for the propagation of these misconceptions. The consequences of this are that students are shown mitochondria represented as only somewhat smaller than nuclei, and structures such as ribosomes and centrioles are shown as though they were visible at the same level of magnification. Even 3D multi-coloured cell diagrams were found by Vlaardingerbroek et al. (2014) to depict organelles incorrectly as similar in size regardless of their true scale, which although potentially useful for the memorisation of cell characteristics, is scientifically incorrect and conceptually misleading. The authors suggested that the use of teaching methods which give attention to the building of visual representations of objects at the micro and nano-levels (such as a virtual environment where scale can be manipulated) may help students avoid harmful misconceptions and build appropriate conceptual models. The role of textbooks and diagrams in perpetuating misunderstandings and misconceptions is discussed further in Section 2.1.2.2.

2.1.2.1.2 Understanding Randomness

Several studies have provided insights into students' difficulties understanding randomness in cell biology, and the misconceptions that students hold on the topic of randomness (Friedler, Amir, & Tamir, 1987; Lander, 2007; Malinska, Rybska, Sobieszczuk-Nowicka, & Adamiec, 2016; Odom, 1995; Sanger, Brecheisen, & Hynek, 2001; She, 2004). Garvin-Doxas and Klymkowsky (2008) for example, investigated student assumptions whilst developing the Biology Concept Inventory (a test of biological knowledge) and found an array of difficulties and misconceptions. Examining more than 500 college student responses and 28 thematic interviews, the authors found that many difficulties stemmed from poor understanding and misconceptions of random processes. Students showed an underlying contradictory belief that whilst biological systems were very efficient, random processes were not, therefore creating a misconception that cell processes are unlikely to be random due to their ‘efficient’ nature. These beliefs prompted students to propose their own ‘rational’ explanations for processes with seemingly random elements. These explanations often mistakenly involved a ‘driver’ to take agency over the process, removing elements of randomness. An example of a common misconception in cell biology was the belief that diffusion could only take place with the presence of a concentration gradient and would cease should that gradient disappear.

The understanding that random processes often take place in cell biology and create complex and sometimes counterintuitive results was absent for students in Garvin-Doxas and Klymkowsky (2008), even for those who had completed multiple biology courses. Professional microbiologists have also been shown to hold misconceptions about random processes. For example, Lander (2007) found in a review of the literature on morphogen gradients that microbiologists often incorrectly understand the potential consequences of the random movement of diffusion, often equating the macroscopic “ballistic” view of movement with a microscopic “diffusive” process. This highlights the need to challenge misconceptions of random processes early on in science education to avoid misunderstandings in further education.

Diffusion and osmosis are featured heavily in studies examining students’ understanding of random processes, and are regarded as some of the hardest biological concepts to grasp (Malinska et al., 2016; Sanger et al., 2001; She, 2004). Odom (1995) found evidence that even after instruction, secondary biology students and biology undergraduates continued to hold misconceptions about these topics. Using a multiple-choice test, Odom (1995) discovered misconceptions spanning from secondary to college level education on topics including the randomness of matter, concentration and tonicity, the influences of life forces on diffusion and osmosis, the kinetic energy of matter, and the processes of diffusion and osmosis. For example, Odom (1995) found that some students believed that particles move because they get too crowded in one area, a finding which has been replicated in further research (Odom & Kelly, 2001). Odom (1995) also found that students thought that if dye molecules stopped moving in water they would fall to the bottom. This misconception has been identified in other research (Sanger et al., 2001), with some students specifying gravity as the driving force for this process (She, 2004). An additional misconception found in Odom (1995) was that dye molecules spread in water because they separate into smaller particles, which was replicated in further research (Odom & Kelly, 2001). Other misconceptions identified in the literature include that particles in areas of greater concentration are more likely to bounce to other areas (Odom & Kelly, 2001), that salt absorbs water from the central vacuole of plant cells (Odom & Kelly, 2001), that dye and water molecules stop moving once they're mixed (Sanger et al., 2001), and that fragrant air and dye molecules dissipate by bouncing off one another (She, 2004).

Specific difficulties in the understanding of osmosis were found by Friedler et al. (1987), who used prior learning inventories, self-report knowledge inventories, true/false tests, definitions and clinical interviews to explore 500 secondary school students' perceptions and misconceptions. Misconceptions included that molecules possess an anthropomorphic 'drive' to move along a concentration gradient, and that once equilibrium is met then molecules will stop moving. The results corroborated previous findings on the apparent difficulty of the topic for this age group and led the authors to suggest that computer simulations may help in illustrating the micro-level phenomena involved. A more recent study by Malinska et al. (2016) looked at 105 second-year undergraduate students' understanding of osmosis before and after lectures on plant physiology, and found that their results corroborated much of the previous literature. It was found that knowledge of diffusion and osmosis was poor and contained numerous misconceptions, often exacerbated by inaccurate information presented in textbooks. Misconceptions identified included that plasmolysis occurs in animal cells, that osmosis only occurred in living organisms, and that osmosis referred only to water and diffusion only to gases. Misunderstandings were also found regarding the semi-permeability of biological membranes, which is a topic that has been identified as problematic in previous research (Dreyfus & Jungwirth, 1989; Flores et al., 2003).

The literature has identified common and widespread misconceptions concerning concepts of magnification and randomness in cell biology, which create a barrier to learning in a topic which is important for the understanding of biology as whole (Verhoeff et al., 2008). Reasons for why misconceptions are prevalent in the topic of cell biology have been suggested, such as the learning materials and how information is presented in the classroom, which will be discussed in the next section.

2.1.2.2 Presentation of cell structures and issues with visualisation

The literature has shown that molecular biology in science education presents widespread difficulties in topics including cell structure and function, macromolecular structure, size and scale, anthropomorphism and randomness (Dreyfus & Jungwirth, 1988; Flores et al., 2003; Malinska et al., 2016). Studies exploring students' understanding of structure and function of cells across age groups suggest that most students find these topics difficult to conceptualise (Dreyfus & Jungwirth, 1988; Flores et al., 2003; Westbrook & Marek, 1991). Furthermore, difficulty conceptualising the relative and absolute sizes of cells results in confusion between sub-cellular, cellular, and multi-cellular concepts, which in turn has been shown to be detrimental to the understanding of biological processes such as diffusion (Westbrook and Marek, 1991).

Textbooks and diagrams are some of the most important resources in science education (Malinska et al., 2016), and pictorial representations are used heavily in the learning of cell biology. Textbooks, however, have been found to contain representations of cells which can lead to, or fail to dispel, misconceptions including those pertaining to concepts of cell physiology, metabolism and structure (Malinska et al., 2016; Storey, 1990, 1991, 1992). For example, it has been suggested that representations of cells may be related to misconceptions including the membrane as a static rather than a fluid system (Storey, 1990), restricting osmosis to water molecules/ liquid only (Malinska et al., 2016), and that enzymes work only by the lock and key mechanism (Storey, 1992). Additionally, inaccurate pictorial representations used in textbooks may contribute especially to commonly held misconceptions regarding size and scale at a cellular level, as students have been found generally to view visualised simulations as realistic depictions of the phenomena they represent (Harrison & Treagust, 2000).

In a review of the educational challenges of molecular life science, Tibell and Rundgren (2010) suggested that the need for visualisation in learning cell biology has prompted some students to use metaphors to facilitate visualisation of relevant concepts and processes. The use of metaphors however can give rise to misunderstandings regarding anthropomorphism (e.g. the cell 'knowing' what to do) as previously mentioned (Bartov, 1978; Dreyfus & Jungwirth, 1988; Flores et al., 2003; Friedler et al., 1987; Zohar & Tamir, 1993). The authors concluded that the key to understanding in this topic was the effective use of visualisation and the subsequent ability to model abstract and complex content regarding the molecular world. Consequently, commonly misunderstood relationships between cell structures and their functions may be challenging for students with lower spatial ability who are not able to integrate them into the overall picture of the cell (Flores et al., 2003). The role of spatial ability in science learning is discussed further in Section 2.2.

2.1.3 Possible solutions and the use of haptics

The literature has presented several possible reasons for the difficulty of understanding magnification and random concepts such as diffusion and osmosis, including the demand for abstract reasoning (Friedler et al., 1987), the need to understand the relationship between macro-and micro-systems (Johnstone & Mahmoud, 1981) and the requirement for students to visualise and think about chemical processes at the molecular level (Oztas, 2014). The aforementioned literature has resulted in recommendations for the improvement of learning in cell biology. Flores et al. (2003) suggested additional classroom features such as experiments and simulators to support the construction of an articulated cell and representations of cell processes. Tibell and Rundgren (2010) recommend similar strategies to benefit learning in the classroom, such as using less stylized and more realistic images to avoid misconceptions.

Several studies have recommended the use of technology simulating direct contact with these previously unobservable processes to correct common misconceptions (Flores et al., 2003; Meir, Perry, Stal, Maruca, & Klopfer, 2005; Odom, 1995). Computer-generated visualisations have been suggested to promote more effective learning of visually and spatially complex topics (Rundgren & Tibell, 2010) as virtual environments can introduce new modalities to the learning process, which may facilitate learning by allowing the integration of more complex or cognitively demanding knowledge (Section 2.3.3). With advancements in affordable technology, it is now possible that interactive virtual environments can be used in the classroom as various interactive software models of cells and processes are developed (e.g. Borchert et al., 2013; Wurtele et al., 2010). Some success in using interactive software for correcting misconceptions was found by Meir et al. (2005), who used simulated molecular-level experiments to teach diffusion and osmosis. However, the use of a simulated cell in this instance resulted in an increased understanding of only one misconception (directionless movement) out of eight identified in their literature review. Certain unrealistic features of the cell and related processes were identified as possible factors in its limited success, such as the unrealistic simplification of the number of molecules.

Despite the increased use of VR in education, schools who use this type of software in classrooms (see for example R. Johnson, 2011) continue to encounter challenges in deeper-level understanding. Teachers reported a persistent difficulty in understanding scale and cellular processes, despite successes in understanding cell structure and function. These challenges are similar to those found with the use of 3D diagrams, where unrealistically proportioned cells are found to increase knowledge of structure and function, but fail to foster understanding of scale or processes that span across different levels of magnification (Vlaardingerbroek et al., 2014).

It has been suggested however, that computer-based visualisations of abstract concepts frequently make use of simplified models of structures and processes which students often take literally, creating the potential for over-simplified misconceptions (Wellington, 2004). Addressing the dangers of learning misconceptions through simplified computer-based visualisations, Hennessy, Deaney, and Ruthven (2006) suggested that this issue could be alleviated through the role of the teacher, who could intervene to add context, address misconceptions and highlight the limitations of computer models to students. Further research focused on the use of haptics in relation to visualisation in science education is discussed in Section 2.3.

3D virtual environments introduced in schools have been suggested to provide only surface-level learning or do not fully take advantage of the unique features VR can offer, as visual information predominates often when multi-sensory information could be utilised (Mikropoulos & Natsis, 2011). Incorporating other senses in learning using VR may be especially beneficial for complex biological information. For example, using visual and haptic information within a virtual environment would allow students to directly experience cellular phenomenon in a more concrete manner, possibly allowing students to better visualise abstract processes and structures and avoid metaphor-based misconceptions. The ability for haptics to provide multisensory cues and immerse students in previously inaccessible phenomena has been suggested as beneficial for complex and abstract topics such as cell biology (Rundgren & Tibell, 2010). Evidence for the use of haptics for improving learning is discussed further in Section 2.4.2.

2.1.4 Summary and conclusion

The literature has shown that misunderstandings and misconceptions in cell biology are present throughout all levels of science education, and misconceptions have been identified concerning topics of magnification/size and scale, randomness (including diffusion and osmosis) and visualisation of cell structures (Dreyfus & Jungwirth, 1989; Flores et al., 2003). It is suggested that the ability to visualise molecular structures, systems and processes is instrumental in understanding cell biology (Friedler et al., 1987; Johnstone & Mahmoud, 1981; Oztas, 2014), and research has recommended the use of educational aids and strategies to support the visualisation of cells and cellular processes. Suggestions include using more realistic, less stylised representations (Meir et al., 2005; Tibell & Rundgren, 2010) and utilising 3D computer models and VR to allow direct access to typically unobservable phenomena (Flores et al., 2003; Friedler et al., 1987; Tibell & Rundgren, 2010). The addition of haptic sense may be especially beneficial for learning in this complex topic by providing direct manipulation and additional sensory information. The literature concerning misconceptions and misunderstandings in cell biology therefore suggests that the use of a 3D virtual environment in classrooms may be beneficial for learning cell biology, and a system capable of allowing direct manipulation of unobservable phenomena, with the addition of the haptic sense, could provide learning benefits previously unavailable in the classroom.

In the development of VR and haptic systems for science education however, the role of spatial ability in learning in science must be considered. The following section will discuss the importance of spatial ability in science learning.

2.2 Spatial ability and learning in science

Research has shown the importance of spatial ability for learning in science, technology, engineering, and mathematics (STEM) education (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). For example, the ability to visualise and manipulate objects in the imagination is known to be crucial for learning in science (Gilbert, 2005; Tuckey & Selvaratnam, 1993), and the translation of 2D to 3D has been suggested to be an important spatial concept in successful STEM learning (Taylor & Hutton, 2013; Wu & Shah, 2004). In this section, research regarding the importance of spatial ability in STEM learning will be explored, as well as the relationship between spatial ability and gender and how this may be related to a gender disparity in science education.

2.2.1 Spatial ability in STEM education

Spatial ability has been defined as skill in "representing, transforming, generating, and recalling symbolic, non-linguistic information" (Linn & Petersen, 1985, p. 1482). High spatial ability has been associated with success in cognitively demanding occupations in fields such as engineering, chemistry, physics and surgery (Shea et al., 2001), and it has been suggested that spatial skill can determine progression in scientific domains (Gardner, 1993). Spatial ability has also been associated with successful learning in STEM fields. For example, Lord and Rupert (1995) found that in a spatial ability paper-folding task, students of scientific subjects scored more highly than both the national average and students studying other subjects. However, this study does not specify whether students with higher spatial abilities were drawn to science or whether students studying science have increased their spatial ability through scientific learning.

Correlational studies have demonstrated links between spatial ability and performance in several STEM disciplines, including mathematics (Guay & McDaniel, 1977; I. M. Smith, 1964), engineering (Devon, Engel, & Turner, 1998), physics (Kozhevnikov, Motes, & Hegarty, 2007) and chemistry (Pribyl & Bodner, 1987). However, caution should be applied in interpreting these studies, as although many of them have found significant correlations after controlling for general intelligence, sample sizes are generally small and most correlations are small in effect size (Hegarty, 2014).

There is longitudinal evidence, however, that spatial ability can be predictive of success and overall participation in science education. Shea, Lubinski and Benbow (2001) followed the progress of 321 intellectually talented students over 20 years, and found that spatial ability provided unique information for predicting self-selected educational tracks. The authors found that those with high spatial ability at age 13 were more likely to prefer mathematics/science to other high school subjects, were more likely to earn undergraduate and graduate degrees in STEM, and more likely to engage in STEM-related occupations two decades later. Additionally, Lubinski and Benbow (2001) conducted a discriminant function analysis, which showed that spatial ability accounted for a statistically significant amount of additional variance beyond mathematical and verbal reasoning abilities in these predictions.

A criticism of Shea, Lubinski and Benbow (2001) is that the sample was not randomised, but the result of a talent search of highly able and motivated students. To address this issue, Wai et al. (2009) utilised longitudinal data gathered from over 400,000 randomly sampled students. This study investigated the impact of spatial ability on STEM achievement and found that those with degrees in STEM fields and those who had pursued scientific occupations had higher spatial abilities at adolescence than those with non-STEM degrees. For example, participants who had earned a doctorate in the physical sciences scored 0.45 standard deviations higher in spatial ability than the mean, whereas those in the humanities scored -0.15 standard deviations below. This study supported the findings of previous research, further suggesting that high spatial ability is characteristic of those who achieve well in STEM subjects.

2.2.2 Gender disparities in spatial ability

Research has consistently found spatial ability to be related to academic achievement in STEM subjects, and has been described as an essential component for success in STEM learning (Hegarty, 2014). However, there is evidence of gender disparity in aspects of spatial ability, which may have educational implications in these subjects. Maccoby and Jacklin (1974), in a review of the effects of gender on cognitive abilities, concluded that a male advantage in visuospatial ability was already well established. However, to assess the magnitude of these reported gender differences, Hyde (1981) applied meta-analysis techniques to the studies cited by Maccoby and Jacklin's review and found that differences were smaller than previously thought; only 5% of the variance in the spatial tasks were accounted for by gender alone.

A later meta-analysis by Linn and Peterson (1985) aimed to examine the magnitude, nature and age of occurrence of gender effects on spatial ability by collecting effect sizes from 172 papers published since 1974. Three categories of spatial ability were identified: spatial perception, mental rotation, and spatial visualisation. The meta-analysis found that both spatial perception and mental rotation were easier for males, with spatial visualisation equally difficult for males and females. The selection process of these categories has been criticised, as there was some overlap in categories and no way to determine, for example, whether participants utilised spatial visualisation alone on tests designed to require spatial visualisation rather than in combination with other subcategories (Caplan, MacPherson, & Tobin, 1985). Alternatively, the role of mental rotation in gender differences in spatial ability has been supported by a meta-analysis by Voyer, Voyer, and Bryden (1995), who also found a male advantage in tasks measuring mental rotation. Mental rotation tasks involve maintaining a 3D figure in working memory whilst simultaneously transforming it (Halpern et al., 2007). This facet of spatial ability has since been reported to produce sex differences of up to one standard deviation

(Masters & Sanders, 1993; Nordvik & Amponsah, 1998), suggesting that this skill especially should be considered in identifying gender differences in spatial ability.

The gender differences in spatial ability shown in the literature present potential issues for females in STEM education, which has been demonstrated by a male advantage in maths and science. For example, Reilly, Neumann, and Andrews (2015) conducted a meta-analysis using data from the US National Assessment of Educational Progress on mathematics and science achievement for students from 1990 to 2011 and found a small male advantage in these subjects, with larger effects for high achievers. It has also been found that mental rotation ability has mediated gender differences in science and engineering test scores, and that larger gender deficits were found on test items that were highly correlated with mental rotations (Ganley, Vasilyeva, & Dulaney, 2014). It has also been suggested that mathematic and visuospatial skill are associated more strongly in females than males, and therefore females may be particularly disadvantaged in maths tasks if they have a lower visuospatial skillset (Halpern et al., 2007).

2.2.3 Summary and conclusion

In summary, the literature suggests that spatial ability may be an important factor in STEM education (Hegarty, 2014), and that there may be some gender differences in spatial ability that can affect how students engage with science (Maccoby & Jacklin, 1974). However, gender differences in spatial ability may be lower than previously thought (Hyde, 1981) and some facets of spatial ability, such as spatial visualisation, show little difference between genders (Linn & Petersen, 1985). Mixed results on the role of spatial ability in STEM learning suggests that it may be an issue to consider when developing learning strategies in these subjects. Additionally, the importance of spatial ability in STEM learning suggests that it should be considered in the development of learning interventions in science education. Furthermore, the increased development of 3D VR and haptic systems for learning complex scientific topics (Sections 2.1.3 and 2.4) may require further consideration due to the need for students to navigate and interact spatially with 3D material.

2.3 Visualisation in science education

It has been suggested that the nature of science education is to train children to become problem-solvers (Garrett, 1987). Researchers and educators have speculated on which methods and elements of cognition are responsible for success in learning science, but one element is known to be an effective problem-solving tool: visualisation. Visualisation is a subset of spatial ability, which is known to have an important role in science participation and achievement (Section 2.2). This section will discuss what visualisation is, its importance in learning and how it is implicated in this project.

2.3.1 What is visualisation?

There is no academically agreed upon definition of visualisation (Linn & Petersen, 1985), but one definition is “the manipulation of an object or pattern in the imagination" (Kahle, 1983, p. 6). It has also been described as "complicated, multi-step manipulations of spatially presented information" (Linn & Petersen, 1985), and “the mental manipulation of spatial information to determine how a given spatial configuration would appear if portions of that configuration were to be rotated, folded, repositioned, or otherwise transformed" (Salthouse, Babcock, Skovronek, Mitchell, & Palmon, 1990).

Spatial visualisation is thought to be one of the many processes which contribute to spatial ability, having been identified as a category of spatial ability by several early researchers (French, 1951; Fruchter, 1954; I. M. Smith, 1964; Thurstone & Thurstone, 1941), and has since shown to be a consistent factor in spatial research. For example, Linn and Petersen (1985) used a cognitive perspective to identify categories of spatial ability by focusing on the similarities of the processes used for individual spatial test items. Using this process, the authors found spatial visualisation to be a distinct category of spatial ability, along with spatial perception and mental rotation (also discussed in Section 2.2.1). Evidence also comes from Carroll (1993) who conducted a large factor-analytic survey of over 90 data sets, and found strong, consistent evidence for spatial visualisation as a factor of spatial ability.

Spatial visualisation is a category of spatial ability which involves complicated, multistep manipulations of spatial information, and although these tasks can involve processes required for other categories (spatial perception and mental rotations), they are distinguished by the possibility of multiple-solution strategies (Linn & Petersen, 1985). Examples of spatial visualisation tasks include paper folding tasks (Figure 1), or block design tests (Figure 2), which involve using analytic strategy to solve complex problems, often using mental rotation and spatial perception (Linn & Petersen, 1985).

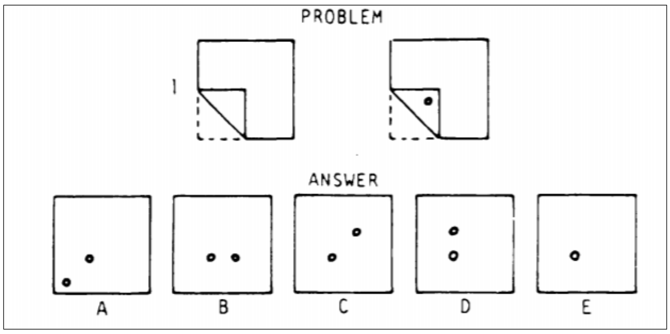


Figure 1: Paper folding task. Students are asked to indicate what the paper will look like when unfolded.

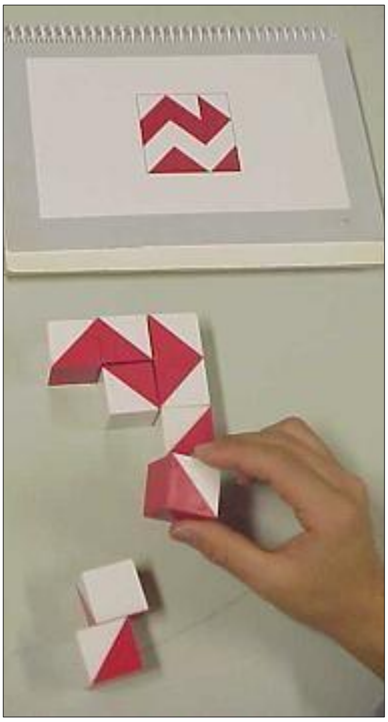


Figure 2: Photograph of a Block Design Test (WAIS III)

2.3.2 The importance of visualisation in science education

Of the senses, educational research has shown that visual perception is the most developed sense and is an important method in learning (Sekuler & Blake, 1985). In education, visualisation has been suggested to support understanding of complex processes by assisting the conversion of abstract concepts into specific visual objects capable of being mentally manipulated (McClean et al., 2005). Consequently, visualisation is considered to be an important cognitive skill for understanding complex and abstract structures and processes in science (Gilbert, 2005). Due to the unobservable and abstract nature of some scientific concepts, models are often used to make abstract concepts 'visual', and therefore easier to conceptualise. Models often represent phenomena spanning several levels of representation (such as microscopic, sub-microscopic and symbolic), and the ability to switch between these levels of representation is thought to be important in successful learning in science (Gilbert, 2005). For example, fluidly switching between modes and levels of representation in chemistry seems to be characteristic of expert chemists, who use this skill to easily to understand complex models and concepts (Kozma, Chin, Russell, & Marx, 2000; Kozma & Russell, 1997). The ability to switch between modes of representation (cellular and sub-cellular) is important for understanding processes too small to observe directly (Arroio, 2012). Therefore visualisation is particularly important in understanding cell biology due to the abstract, unobservable nature of the topic, and the crowded, complex structure of the cell (Petsko & Ringe, 2004).

There are theories which suggest that existing visuo-spatial ability may affect how people benefit from graphical representations in learning. For example, Hays' (1996) ability-as-compensator hypothesis would suggest that those with low spatial ability would benefit from graphical representations such as the 3D cell in this project, as they struggle to visualise their own. Additionally, research has shown that interacting with 3D models has a positive impact on comprehension of 3D computer visualisations for those with lower spatial ability (Keehner et al. 2004). Conversely, Huk (2006) suggested that according to Dual Coding Theory (discussed in detail in Section 2.3.3), a 3D representation of a cell presents extra graphical information that may overload the visuo-spatial memory of those with low spatial ability, causing a detriment to learning. This 'ability-as-enhancer' hypothesis would suggest that those with high spatial ability might benefit from learning with 3D materials such as models and animations, while learners with low spatial ability might not.

A meta-analysis on the influence of spatial ability on learning with visualisation was conducted by Höffler (2010), who found an overall medium effect favouring those with high spatial ability compared to those with low special ability when using visualisations, suggesting that for the use of visualisations, a high spatial ability is beneficial. Although this finding would support the ability-as-enhancer hypothesis, Höffler (2010) also found that the strength of the effect differentiated with certain factors. It was found that the effect of high spatial ability on learning with visualisations was stronger in non-dynamic visualisations than dynamic, suggesting that high spatial ability is beneficial when learning with non-dynamic visualisations. However, there may be a compensatory effect for dynamic visualisations on those with low spatial ability (consistent with the ability-as-compensator hypothesis). Overall, the findings from Höffler (2010) supports that spatial ability may be important in learning using visualisations, but the size of the effect of high spatial ability depends on factors such as dynamicity or dimensionality. Spatial ability may be an important aspect in learning involving graphical representations and 3D models and therefore may influence the ability to learn through a 3D haptic system. Consequently, the literature would suggest that spatial ability should be considered as a potentially relevant factor in this project.

2.3.3 Dual Coding Theory (DCT)

A theory that may account for the beneficial effects of visualisation in learning is Dual Coding Theory (DCT) (Paivio, 1969). DCT splits cognition into two systems: a verbal system used for language, and a non-verbal/imagery system used for non-linguistic objects and representations. These systems are suggested to contain two types of representational units (logogens and imagens) which activate upon recognising, manipulating, or thinking about words, object, or situations. Logogens and imagens also correspond to the senses, distinguishing between visual, auditory, and haptic feedback. Verbal and visual coding systems are separate but interconnected, able to work independently, in parallel, or through interconnections between them. As such, the verbal code may dominate certain tasks where the non-verbal code dominates in others. Both coding systems are used together frequently, with non-verbal systems providing alternative internal representations of events, allowing more effective problem solving. DCT may account for the power of images in memory and learning (Paivio, 2014), as well as the beneficial effect of the combined coding of sensory information through both verbal and visual means in education.

Evidence for the effectiveness of dual coding in learning was originally presented by Paivio (1969), who provided participants with rapid sequences of words and images before asking them to recall the information in any order. For general free recall, it was found that participants were better at recalling images. In contrast, participants recalled words more readily than images when asked to remember a sequence of information, suggesting that verbal and visual information are processed differently and supporting DCT. Additionally, Rohwer (1970) reviewed early studies regarding the role of imagery in children's learning and concluded that the ability for children to benefit optimally from verbal representations develops earlier in their learning processes than the ability to benefit optimally from imagery, suggesting a distinction between the processing of verbal and pictorial information. Within literacy research, DCT has been supported by studies demonstrating the beneficial effect of coding multiple representations in domains including decoding and comprehension (Sadoski & Paivio, 2004, 2007), spelling (Sadoski, Willson, Holcomb, & Boulware-Gooden, 2004), and story recall (Gambrell & Jawitz, 1993). Additionally, for the retention of verbal items in word lists, dual coding verbal information with imagery has been shown to result in an additive effect (Paivio, 1975; Paivio & Csapo, 1973). Furthermore, a review by Sadoski (2005) concluded that dual coding both verbal and pictorial representations in vocabulary learning had a beneficial effect for English (Levin, 1993; B. D. Smith, Miller, Grossman, & Valeri-Gold, 1994; B. D. Smith, Stahl, & Neil, 1987) and other languages (Avila & Sadoski, 1996; Rodriguez & Sadowki, 2000).

Research concerning the learning of motor skills has also supported the role of DCT in successful acquisition. A meta-analysis by Driskell, Copper, and Moran (1994) reviewed studies regarding whether mental imagery enhances performance of a task, which typically involved imagining a specific action whilst being guided by verbal information. The authors found significant results after reviewing 35 studies representing the behaviour of 3,214 participants, concluding that mental practice offers the opportunity to rehearse behaviours and to code behaviours into both words and images to aid recall, which is consistent with what DCT would suggest.

Evidence for DCT has also been found concerning the use of olfactory information in conjunction with verbal and visual representations. Lyman and McDaniel (1990) presented participants with olfactory stimuli in combination with visual and/or verbal representation to determine the effects of dual coding of multiple representations on odour recall and recognition. After a retention period of a week, a free recall and odour recognition test were conducted, where the authors found that those provided with multiple representations were more successful, with those presented with visual, verbal, and olfactory information performing more favourably than control groups of either olfactory or verbal representations in isolation. The findings from Lyman and McDaniel (1990), therefore provided evidence for the additive effect of the coding of multiple representations on recall and the independent contribution of different modalities for memory.

The research discussed in this section has shown how the beneficial effect of using multiple representations has been demonstrated repeatedly, supporting DCT (Paivio, 1969) as an explanation for the importance of visualisation in science education.

2.3.4 Summary and conclusion

Visualisation has been shown to be a consistent and measurable factor of spatial ability (Carroll, 1993; Linn & Petersen, 1985) and is thought to be an important skill for learning in science (Kozma et al., 2000; Kozma & Russell, 1997; McClean et al., 2005; Petsko & Ringe, 2004). The literature suggests that visualisation allows the modelling of complex scientific concepts (McClean et al., 2005), facilitating the understanding of abstract ideas and complex scientific concepts. Visualisation may also be an important skill allowing students to switch between different modes of representation, which has been shown to be important in understanding complex or unobservable scientific concepts such as those found in cell biology (Arroio, 2012; Gilbert, 2005).

DCT (Paivio, 1969) presents an explanation for the importance of visualisation in learning. DCT suggests that, at a systematic level, the use of imagery is beneficial for memory due to the combined coding of visual and verbal information, which is supported by studies finding significantly positive and additive results in the use of multi-sensory representations (Avila & Sadoski, 1996; Gambrell & Jawitz, 1993; Levin, 1993; Paivio, 1969, 1975; Paivio & Csapo, 1973; Rodriguez & Sadowki, 2000; Rohwer, 1970; Sadoski & Paivio, 2004, 2007; Sadoski et al., 2004; B. D. Smith et al., 1994; B. D. Smith et al., 1987). This research has shown that coding using multiple representations such as verbal, visual, and olfactory information can be beneficial for learning, and according to DCT the use of haptics (touch) would similarly benefit. Section 2.4 will discuss the use of the haptic sense in learning and the rationale for the use of haptics in science education in particular.

2.4 Haptics in science education

The use of technology enhanced learning (TEL) relates to the application of information and communication technologies to teaching and learning (Kirkwood & Price, 2014). Within science education TEL has been shown to increase motivation (Deaney, Ruthven, & Hennessy, 2003), support visualisation skills (Piburn et al., 2005), support the learning of difficult concepts and enable hypothesis testing in areas of science where direct manipulation of real-world objects is impossible (Rutten, Van Joolingen, & Van Der Veen, 2012).

Technology with the potential to allow the manipulation and exploration of a 3D space has been identified, which the literature suggests may be beneficial to learning in subjects containing complex and unobservable phenomena. This ‘haptic’ technology uses 3D visual information and touch interfaces allowing tactile feedback for exploration within a 3D space. It is possible that access to 3D visual and haptic information may aid learning in science, facilitating visualisation which has been shown to be an important skill in science learning (Section 2.3.2). Moreover, multimodal learning has been suggested to increase engagement and understanding in classrooms (Sankey, Birch, & Gardiner, 2011), further supporting the use of haptics for difficult subjects. This section will discuss what haptics are, how they may be helpful in learning science, and the literature concerning their role in education thus far.

2.4.1 What is haptics?

Originally, the term *haptic* comes from the Greek *haptikos*, meaning 'to touch'. In the broadest sense, haptics refer today to the study of the interactions by touch between humans and an external environment (Minogue & Jones, 2006). In the context of this research however, haptics refers specifically to enabling a user to touch and feel VR, sensing and manipulating through touch. This technology can be used to deliver tactile or force feedback through supporting software to those who interact with virtual environments, allowing users to 'feel' and manipulate 3D virtual objects in space (Kapoor et al., 2014; McLaughlin et al., 2002). Haptic devices can come in several forms, including joysticks, paddles, gloves or robotic arms, and are used to interact with the virtual space and provide touch feedback to the user. The implications of utilising 3D haptic devices will be explored in the following section to determine why haptics may be useful in learning and in particular, the learning of science.

2.4.2 Why might haptics be useful in learning?

Within the literature on the use of haptics in education, there are two prominent theoretical underpinnings for how and why haptic devices may aid learning: Embodied

Cognition and Additional Touch Sensory Channel theory (Zacharia, 2015) which incorporates Dual Coding (Paivio, 1969) and Cognitive Load theories (Sweller, 1994). Below is a brief overview of each theory and a discussion of their relevance to haptics in education.

2.4.2.1 Embodied Cognition

2.4.2.1.1 What is Embodied Cognition?

The Embodied (or grounded) Cognition theory (Barsalou, 2008) takes the view that understanding is constructed by information represented within the sensory and motor systems. This theory stresses the importance of perception in conceptual learning by bringing attention to the knowledge that can be gained from physical interactions between a person and the external environment (Barsalou, 2008). According to this theory, when an experience occurs the brain captures information across the sensory modalities and integrates them to create a multimodal representation stored in memory. Later, when knowledge of this experience or objects relating to this experience are needed, multimodal representations created during the original experience are reactivated. A simple example of this would be being presented with the word ‘hammer’ which would facilitate not only the retrieval of the concept of a hammer, but also the sensory and motor information that would mediate the use of the hammer due to embodied cognition (Mahon & Caramazza, 2008). Consequently, some researchers consider that feeling and using sensorimotor experiences can allow learning of abstract concepts. For example, the knowledge of how hard to kick a ball to another person without explicitly calculating force, distance or friction, or how to balance on a bicycle is often hard to explain due to their abstract nature (Hallman, Paley, Han, & Black, 2009). Embodied Cognition would suggest that as these people interact with the environment, a tactile embodied knowledge is acquired of how those materials and systems work and this knowledge can be applied in new contexts.

2.4.2.1.2 Embodied cognition in learning

The Embodied Cognition theory can be applied to science education, emphasising the role of perceptual experiences in understanding abstract concepts by using touch. Whilst attempting to learn abstract, intangible concepts, imagining them is often difficult with no direct experience as they are rarely able to be perceptually simulated in the mind (Hallman et al., 2009). Intangible concepts are common in science education due to many phenomena (such as forces) being unobservable, and some objects being too small or big to conceive concretely, highlighting the relevance of Embodied Cognition for learning such concepts.

Sensory information including touch feedback can therefore become cognitive anchors for understanding abstract concepts, building schemata of haptic information grounded in the haptic sense unable to be recreated by any other type of sensory modality (Reiner, 2009). These haptic schemas could lead to the construction of conceptual metaphors, which learners can use to develop a deeper understanding of, or to ground scientific concepts (Zacharia, 2015).

Evidence for haptic schemas can be found in neuroimaging studies on category related brain activation, which show that sensory and motor activation can accompany conceptual processing. For example, fMRI images of monkeys viewing graspable tools showed activation in the left ventral premotor cortex, even with the absence of any subsequent motor activity, whereas pictures of objects with no motor component (e.g. animals and houses) did not elicit this activation (Chao & Martin, 2000). Consistent activation was also found in human areas of the brain concerned with motion after being shown pictures of, naming or answering questions about tools, suggesting semantic object information is represented in networks including those storing information on motion (Chao, Haxby, & Martin, 1999). Moreover, studies regarding the pattern of brain activation in participants viewing pictures of tools compared to pictures of animals suggested the use of regions that mediate knowledge of object motion and use (Perani, Schnur, Tettamanti, Cappa, & Fazio, 1999). Furthermore, it has been shown that our own mental imagery can elicit activation of motor related brain areas. W. Richter et al. (2000) used fMRI to measure brain activity during a mental rotation task requiring them to imagine the rotation of an object and found activation of several motor areas in all participants completing the task. This suggests that regions concerned with the physical movement of objects were activated by the self-created visual imagery of rotation, further supporting the activation of haptic knowledge as embodied cognition.

Behavioural research has also shown that certain representations are stronger in those with more experience and depth of related background, supporting evidence of embodied cognition. Theories of embodied cognition assume that representations of objects include sensorimotor information, and so it would follow that if people have not experienced the sensorimotor information concerned with the object, then they may lack certain representations. This assumption has been supported by research from Holt and Beilock (2006), who used novice and expert hockey players to read sentences describing every day or sport-specific situations and then decide whether a pictured item (either matching the action implied in the previous sentence or not) was mentioned in the preceding sentence. The authors found that every participant responded most quickly to items that matched the sentence-implied actions for everyday and non-sport-specific actions, however, only expert athletes showed this effect for their respective sport-specific scenarios. The results show that expert (experienced) sports players could differentiate between the same sport specific item in different action orientations, whereas novices could not, suggesting that sensorimotor experience with an object allows for easier possession of representations. This finding supports the Embodied Cognition theory, suggesting that those with tactile experiences with an object can create better representations than those who are visually familiar but lacking sensorimotor experience.

It has been suggested that uniquely haptic information may be able to supplement information from other modalities in order to increase perception or understanding of phenomena, creating a richer multimodal representation and allowing for deeper understanding (Bivall et al., 2011). Abstract concepts such as those common in science education are especially difficult to process by themselves due to the lack of simulations and sensorimotor information available to ground the concept. An abstract concept becomes easier to process if a background situation can contextualise it by providing visual and tactile information (Barsalou, 2008). Lakoff (1990) suggested the use of embodied cognition for abstract concepts may be facilitated by the use of conceptual metaphors, whereby abstract concepts are grounded into perception via concrete domains, allowing them to be embodied. Conceptual metaphors are used frequently in everyday language and has been suggested to help construct conceptual systems (Lakoff & Johnson, 1980). However, there is evidence that metaphors can be problematic in science education, as students often overextend and misapply conceptual metaphors in their learning (Brookes & Etkina, 2007), and poorly chosen metaphors have the potential to induce misconceptions in complex concepts (Winn, 1999; Zhang, Chen, & Ennis, 2019). Therefore, there is some debate about the usefulness of conceptual metaphors, as although they have the potential to contextualise abstract concepts (Lancor, 2014), they also have the potential to be problematic.

2.4.2.1.3 Embodied Cognition with physical and virtual manipulatives

As discussed in Section 2.4.2.1.2, Embodied Cognition theory suggests that that our cognition is created based on the multimodal representation that we acquire from bodily experiences through our senses whilst interacting with the environment (Barsalou, 2008). There is evidence that physically interacting with objects or environments could create a perceptual foundation for abstract learning, which can be seen in studies showing the benefits of physical manipulation in learning. Evidence for the benefits of physical manipulation will be discussed here in the context of embodied cognition, as well as the effect of virtual manipulation on acquiring embodied experiences for the perceptual grounding of abstract ideas.

There is evidence that physical manipulation during experimentation can result in increased learning in science. Research on the benefits of touch in subjects such as mathematics and linguistics have shown the positive effect of physical manipulation on the learning and memory of young children. For example, Bara, Gentaz, Colé, and Sprenger-Charolles (2004) compared the gains in a pseudo-word reading task of children undertaking training designed to develop phonemic awareness. This study incorporated either a Haptic-Visual-Auditory-Metaphonological or Visual-Auditory-Metaphonological exploration of letters into their training and found that performance in the haptic, visual and audio condition was greater than those receiving visual and audio information only. Glenberg et al. (2004) also found that children manipulating toy objects and acting out scenarios referred to in text resulted in better memory of the text material compared to re-reading, also demonstrating the positive impact of haptic manipulation on memory. Additionally, Ramani and Siegler (2008) found that playing linear number board games enhanced young children’s numerical knowledge in four numerical tasks: numerical magnitude comparison, number line estimation, counting, and numeral identification, with gains remaining 9 weeks later. The authors concluded that interactions with physical materials helped children form more advanced mental representations of the linear number line, highlighting the beneficial effect of physical manipulation for children’s learning.

In addition to consistent evidence for the beneficial effects of physical manipulatives, there is also evidence that virtual manipulation can be equally helpful. For example, Zacharia and Olympiou (2011) investigated the effect of physical and virtual manipulation on undergraduates’ understanding of concepts of heat and temperature with four experimental conditions: physical manipulation, virtual manipulation, combinations of virtual and physical manipulation and traditional instruction as a control. The authors found that the experimental conditions were equally effective in promoting students' understanding. The results of this experiment suggested that physical and virtual manipulation were equally effective in benefitting learning. Zacharia and Olympiou (2011) concluded from this study that the important factor influencing learning is not physicality (actual and active touch of concrete material) or embodied information, but manipulation itself.

However, further research challenged the finding from Zacharia and Olympiou (2011) that manipulation is the key factor in learning from physical manipulation rather than physicality. Zacharia, Loizou, and Papaevripidou (2012) compared the use of physical (real materials) and virtual (computer simulation using mouse and screen) materials on learning concepts of balance accounting for student's prior physical knowledge of balance and mass. Physical and virtual manipulation was used to teach students about mass using a balance beam technique, and it was found children learned more from physical and virtual manipulation when they had prior knowledge of how a balance beam behaves; but when the children did not have that understanding, virtual manipulation was not as helpful. The results of this study suggest that physical knowledge of how the learning materials would behave was a prerequisite for the effectiveness of virtual manipulation. Although the results of Zacharia and Olympiou (2011) suggested that manipulation alone was the necessary component for the benefit of physics learning, the results of their follow up experiment suggested that physical, embodied knowledge was an important factor for increased learning. Children in this study did not benefit from virtual manipulation when they did not possess the physical knowledge of how balance beams behave, however, when they did have that knowledge, both physical and virtual manipulation were helpful.

Considering the findings from Zacharia and Olympiou (2011) and Zacharia et al. (2012), Han (2013) conducted an experiment to explore an alternative explanation for explaining the effects of physicality in learning mechanics by focusing on embodiment. For this study, 48 graduate students completed a task learning how gears work. They were split 3 groups: physical manipulation, virtual manipulation, and a control (regular textbook teaching). No differences were found in the learning of those using physical or virtual manipulation, supporting previous studies on the topic. However, when the participants were separated by whether they had prior experience with driving a manual transmission car (involving physical knowledge of gear systems and changes) or not, it was found that those with embodied/physical experience performed better in a test of knowledge on gears. Therefore, this study found that physical and virtual manipulation were equally conducive to students' learning but embodied/physical experience increased performance on tests of knowledge. The findings of this study imply that physicality used in a learning experience should be evaluated in terms of its potential to create embodiment rather than whether it is physical or virtual. Therefore, for the use of embodied cognition in learning, this evidence suggests that physical, embodied experiences are most beneficial during physical manipulation. This then supports the assertion that the embodiment of physical actions could complement the input received from other modalities, enabling students to build richer multimodal representations that support more complex understandings (Bivall et al., 2011).

2.4.2.1.4 Manipulation versus physicality in use of haptic devices

In Section 2.4.2.1.3, the literature revealed some debate on the type of manipulation which allows for greater positive effects on learning, and it was suggested that the effectiveness of using physical versus virtual manipulatives can be unclear (Han, 2013). Han (2013) went further, suggesting that the potential to create embodied experiences during physicality is what is most important in learning, and that the lack of differences found between virtual and physical manipulatives in some studies were due to neither condition providing sufficient extra information available to be embodied over the other.

This suggests that it is not manipulation, but the potential to create embodied experiences from information that is important, regardless of the method of manipulation.

It was suggested by Han (2013) that manipulation without additional physical information may provide an embodied experience by which students may ground abstract information, although their results later found that manipulation alone was not advantageous in learning compared to regular teaching using textbooks. The authors, however, do caution the results should be used with care due to a small sample size and concerns over unequal aspects of testing procedures between control groups. The literature exploring whether manipulation alone in the use of VR interfaces can create embodied experiences to aid learning compared to manipulation with additional haptic perceptual information is limited, however, the literature mentioned in this section suggests that a method of manipulation which utilises additional information that can be used to create an embodied experience (such as feeling forces) may be more appropriate for the utilisation of embodied cognition (Han, 2013; Zacharia et al., 2012; Zacharia & Olympiou, 2011), as it provides additional perceptual experiences with which to ground abstract concepts (Barsalou, 2008) and consequently build richer representations (Bivall et al., 2011).

Relating the literature discussed in this section to this project, both the haptic and non-haptic conditions (Section 3.4.1) in this study will provide manipulation, however only the haptic condition will provide extra perceptual information in the form of haptic feedback from the model (unique to the haptic sense) capable of providing additional embodied experiences. The literature discussed in this section would suggest that according to the Embodied Cognition theory, as the haptic condition will provide additional physicality, the haptic feedback can be embodied resulting in a more complete picture of the phenomena to be transferred to long term memory (Barsalou, 2008; Bivall et al., 2011). Conversely, if haptic feedback does not provide enough additional opportunities for embodied cognition, it is possible that no differences will be revealed between conditions.

2.4.2.1.5 Embodied cognition summary and conclusion

In summary, Embodied Cognition has been introduced as a theory relevant to the use of haptic feedback in learning cell biology. According to Embodied Cognition, when an experience occurs the brain captures information across the sensory modalities and integrates them to create a multimodal representation stored in memory (Barsalou, 2008). It has been discussed that touch feedback which is able to be embodied can provide cognitive anchors for understanding abstract concepts (Reiner, 2009). Evidence for Embodied Cognition was discussed, including fMRI studies demonstrating motor cortex activation with the presentation of associated stimuli (Chao et al., 1999; Chao & Martin, 2000; Perani et al., 1999; W. Richter et al., 2000), and the impact of haptic manipulation on memory (Glenberg et al., 2004; Ramani & Siegler, 2008). Additionally, the literature on the differences found between virtual and physical manipulatives was discussed (Han, 2013; Zacharia et al., 2012; Zacharia & Olympiou, 2011), which suggested that physical and virtual manipulatives are often found to be equally beneficial because they both offer manipulation and physicality, including perceptual experiences which are able to be embodied, enabling students to build richer multimodal representations (Han, 2013; Zacharia et al., 2012). Manipulation without haptic feedback may be able to create embodied experiences, but the addition of haptic feedback (according to Embodied Cognition theory) would provide additional, unique, perceptual experiences in which to ground abstract concepts such as those in cell biology.

This section has discussed Embodied Cognition as a relevant theory regarding the use of haptic feedback in learning. The following section will discuss the Additional Sensory Channel theory (Zacharia, 2015), which also provides a theoretical basis for the potential benefits of haptic feedback in learning.

2.4.2.2 The Additional Sensory Channel theory: Integrating Dual Coding and Cognitive Load theories.

Two theories that offer explanations as to why the addition of haptic feedback may be beneficial to learning are Dual Coding Theory (DCT) (Paivio, 1969) and Cognitive Load Theory (CLT) (Sweller, 1994). Using these theories in conjunction to explain the benefits of supplementing information with haptics has also been referred to as the Additional Sensory Channel theory (Zacharia, 2015).

As discussed in Section 2.3.3, DCT (Paivio, 1969) suggests that there are distinct systems for different sensory modalities that work together, allowing the beneficial effect of the combined coding of sensory information. According to this theory, the addition of the haptic sense would work synergistically with other sensory modes to aid the coding of complex information. CLT (Sweller, 1994) also suggests that whilst learning, an individual's working memory is put under cognitive load as new information is attempted to be processed. Information is commonly processed visually or auditorily, however, haptic devices provide sensory feedback in the form of touch, and it is thought that having a new channel of information in a different modality may help alleviate cognitive load and aid learning. CLT (Sweller, 1994) is discussed in more detail in Section 2.4.4.

DCT and CLT are based on the 'modality principle', which assumes that every modality has its own processing channel within working memory (Millar, 1999) and that by utilising several channels, cognitive load can be split between them thereby facilitating learning (Low & Sweller, 2005). Research has shown that the use of multiple modalities can have a beneficial effect on learning (Bara et al., 2004; Ginns, 2005) and evidence for the modality effect also coincides with the evidence for DCT, as discussed in Section 2.3.3.

The concept of a haptic channel being utilised to lower cognitive load is also present in a proposed cognitive processing model by M. S. Chan and Black (2006), which describes the process of learning by specifically incorporating information presented through auditory, visual and haptic channels. As in the Additional Sensory Channel theory (Zacharia, 2015), the model by M. S. Chan and Black (2006) suggests that effective strategies for information presentation could lower the cognitive load for complex subject matter, dividing information amongst multiple processing channels for more efficient processing. The authors suggest the presence of an additional haptic channel would allow the use of haptic technology as an effective strategy to present information by lowering cognitive load and allowing for more efficient learning. M. S. Chan and Black (2006) offer evidence for this model in their study using a haptic direct manipulation animation method in science education. In this study, 157 school students were taught mechanical energy transfer with either narrative only, narrative with visual, or a haptic-direct-manipulation animation method of information presentation. It was found that the haptic animation provided support which enabled students to better understand the content, reason on ‘what-if’ scenarios and problem-solving tasks and generalise their knowledge to solve problems unaffiliated with the subject they initially learned. The findings of this study suggested that using a haptic channel for learning resulted in benefits for those learning complex material in science and supports the use of a haptic channel to aid information processing.

It has been suggested by Zacharia (2015) that the use of an additional haptic-specific channel to decrease cognitive load may particularly benefit the understanding of particularly complex and abstract topics in science. The author suggested that for information typically presented through visual or audio modalities, but also able to be perceived via haptic information, the load previously bore by one channel can be spread across multiple. For example, spatial perception consists of information such as size and shape which can be gained both visually and haptically, and according to the Additional Sensory Channel theory (Zacharia, 2015), using both modalities would benefit the conceptualisation of abstract concepts by using two information processing channels and lowering the burden of cognitive load on the working memory.

Evidence supporting the role of haptics in lowering cognitive load can be demonstrated in studies showing increased learning during experimentation with the use of physical manipulatives in science which were discussed in Section 2.4.2.1.3 in the context of Embodied Cognition. The findings of those studies were consistent with the Additional Sensory Channel theory (Zacharia, 2015) which would suggest that haptic information would have been processed using the haptic channel, lowering the burden of cognitive load on the working memory and resulting in positive learning gains. Further evidence for the Additional Sensory Channel theory (Zacharia, 2015) involving the use of haptic feedback devices in science education is discussed in Section 2.4.3.

2.4.2.2.1 The Additional Sensory Channel theory summary

In summary, The Additional Sensory Channel theory (Zacharia, 2015) incorporates both CLT (Sweller, 1994) and DCT (Paivio, 1969) theories, which are related by their underlying modality principle (Millar, 1999). The modality principle suggests that different modalities have corresponding information processing channels (Low & Sweller, 2005; Millar, 1999), and DCT and CLT suggest that utilising multiple channels may reduce cognitive load and therefore aid the learning of complex scientific processes (Zacharia, 2015). Evidence for this theory comes from the beneficial use of physical and virtual manipulatives discussed in Section 2.4.2.1.3, and studies supporting the modality principle showing that a combination of modalities are beneficial for learning (Bara et al., 2004; M. S. Chan & Black, 2006; Ginns, 2005).

This section has discussed why haptics may be helpful in learning by considering Embodied Cognition (Barsalou, 2008) and Additional Sensory Channel (Zacharia, 2015) theories. The next section will discuss the use of haptics in science learning so far, including for primary and secondary science education.

2.4.3 Haptics for the learning of abstract concepts in science

Research into the use of haptics in education has grown rapidly as touch feedback technology has developed and become more accessible in recent years (Minogue & Jones, 2006). As such, there is now a varied body of research concerning the impact of using haptic feedback devices in several domains (Escobar-Castillejos, Noguez, Neri, Magana, & Benes, 2016; Minogue & Jones, 2006; Zacharia, 2015). Much of the research in this area began in the acquisition of fine motor skills in the medical and dental fields, a task which is particularly suited to the use of haptic feedback (Shahriari-Rad, 2014). However, much of the emerging research is more specifically targeted at science education and the learning of abstract concepts. This section will discuss research on the impact of haptics on learning in general science education.

There a body of research which has explored the contribution of haptic feedback offered through virtual manipulatives on learning in Science. Research evaluating the use of haptic feedback devices in education is mixed however, with studies finding both positive additions to learning and others finding no significant improvements.

Evidence for the use of haptics in the learning of physics was found by Reiner (1999), who used a haptic trackball interface to allow undergraduate students to feel the force applied by a field on an object. Although the students in this study were unfamiliar with physics, they were able to draw accurate force field representations related to the haptic information they had gained. The author suggests that the computer tactile interface acted as a trigger for access to non-propositional knowledge (such as knowledge gained with embodied cognition), and although the study was exploratory and limited to the use of graduate students, the haptic information was still found to provide a positive addition to the student’s learning experience.

Also within the field of physics education, Hallman et al. (2009) used a haptic joystick device to utilise haptic feedback for graduate students' learning of gears. By comparing a haptic group (which used visual simulation together with a force-feedback device) with a non-haptic group, (which lacked force-feedback), Hallman et al. (2009) found that postgraduate students provided with haptic feedback tested more successfully compared to the non-haptic control group. However, the effect size was small, and the haptic group expressed more negative opinions on utilising the haptic based learning materials, suggesting that either the simulation negatively affected the attitudes of the users, or the users already had negative attitudes towards computer-based learning before the experiment. After finding that children were more comfortable with the technology used in the study than graduate students, the authors suggested that the age of the participants and related discomfort with new technology in this study may have influenced negative post-graduate opinions. The authors concluded that overall, haptic devices in this instance appeared to be a useful addition to the learning of gears and force related subjects, especially for those comfortable using new technology.

Studies finding a positive impact of haptic devices on learning in science have also been found in the biomolecular domain. Brooks, Ouh-Young, Batter, and Kilpatrick (1990) investigated the impact of additional haptic information on a task involving the docking of two biomolecules by comparing performance with a non-haptic, visual-only control. The authors found that those in the haptic group docked the molecule more quickly and had a better understanding of molecular forces and fields than those with visual-only feedback, suggesting that haptic feedback directly aided learning in this task. Similarly, Bivall et al. (2011) and Schönborn, Bivall, and Tibell (2011) explored whether adding haptic feedback to 3D chemical models enhanced students' understanding of molecular bonding. These researchers presented a task involving interactions between a protein and a ligand molecule, assessing a docking activity and a molecule recognition activity respecively. The authors found that the addition of haptic feedback in conjunction with 3D visual information produced faster docking times (Schönborn et al., 2011) and increased understanding of molecule binding, whilst also changing the way in which the students described the structure of these molecules to include more force related explanations (Bivall et al., 2011). The authors concluded in both studies that haptic feedback had provided additional information to students which had benefitted their learning in this topic. In addition, Schönborn et al. (2011) discussed their results in the context of Embodied Cognition, suggesting that a visual and tactile sensorimotor interaction in the macroworld may provide access to constructing knowledge about sub-microscopic phenomena. The authors suggested that a 3D visual display coordinated with haptics offered by a model in the macroworld could provide an embodied experience for understanding perceptual sub-microscopic processes, such as those found in cell biology.

Beneficial effect of haptics in science learning have also been found for concepts in secondary science education. For example, Jones, Andre, Superfine, and Taylor (2003) investigated the effect of haptic feedback on 50 high school students' conceptions of viruses. By combining an atomic force microscope and a haptic device, students could manipulate an ordinarily invisible virus in 3D. The authors compared fully haptic (able to feel shape, surface, stickiness etc.) and limited haptic (able only to feel a flat surface) conditions and found that both increased the students' conceptual understanding of viruses. The authors concluded from questionnaires and interviews that haptic feedback appeared to make students more engaged and interested in learning, however, no difference in performance could be found between the two conditions, suggesting that haptic feedback alone did not result in increased learning. The authors suggested that a small sample size may have affected the power of the study to detect differences between groups and concluded that the exploratory nature of this study could not firmly decipher the direct effect of haptics on learning outside of increased engagement in the task.

To further explore the role of haptic feedback in the learning of cell biology, Jones, Minogue, Tretter, Negishi, and Taylor (2006) compared haptic devices with differing levels of sensitivity: a low sensitivity haptic joystick, a higher sensitivity Phantom haptic device and a non-haptic mouse as a control. Using computer programs to display 3D viruses combined with pre-recorded sections from the aforementioned atomic force microscope, middle and high school students were asked to identify viruses. The authors found that both haptic devices were more immersive than the non-haptic mouse, were more enagging and fostered more explanatory analogies from students during the task, which was thought to be a sign of increased understanding. It was also found that as sensitivity increased, more haptic terms were used to describe the virus. Although there were no significant differences in the number of viral characteristics identified between the two haptic devices, the learning gains present in both haptic conditions suggest that the presence of any haptic data was a positive addition. Again however, the authors identified the small sample size as a limitation to this research and caution the generalisation of these results to a wider context.

Also investigating the effect of haptic devices in secondary level science education, Minogue and Jones (2009) used the subject of permiability in cell membranes to test the effectiveness of haptic feedback on learning. Students were either provided with visual and haptic feedback or visual feedback alone, and were tested with the SOLO taxonomy (Biggs & Collis, 1980) prior to and after their investigtions on aspects of membrane permiability. The authors found that those with visual and haptic feedback tested more successfully and were able to integrate concepts more easily than those with visual feedback alone, which the authors suggest is evidence that haptics may lead to deeper processing in the learning of science. However, the authors do caution that the application of the SOLO taxonomy does not guarantee an accurate and complete account of what was learned, and that to determine a more accurate picture of the benefits of haptics in learning, a larger range of assessment tasks should be considered.

There is growing evidence from research showing visual and haptic feedback to be beneficial in the engagement and learning in several disciplines and accross levels of science education (Zacharia, 2015). However, there is contradictory research which has found no difference in learning gains between haptic and non-haptic feedback in the classroom. Some of these studies are from the same research teams that have published studies showing positve results for haptics in education. For example, despite other successes in this research topic (Bivall et al., 2011), Bivall et al. (2007) found that although students receiving haptic feedback took less time to complete tasks and reported deeper understanding of the forces involved, there was no increase in conceptual knowledge overall, leading the authors to conclude that there was no obvious advantage for haptic feedback in this study. Similarly, despite earlier supportive findings for the use of haptics (Jones et al., 2003; Jones, Minogue, Oppewal, Cook, & Broadwell, 2006; Jones, Minogue, Tretter, et al., 2006), Minogue et al. (2006) failed to find a difference in educational gains in their study comparing haptic and 3D visual feedback to visual-only feedback in a sample of 80 middle school students on the topic of animal cells. Minogue et al. (2006) hoped to increase the students knowledge of the structure, organelles and membrane properties of the animal cell by introducing haptic feedback in their learning. However, the authors found that learning gains were equally large in both conditions, despite students finding the haptic device less frustrating and easier to navigate the 3D space with. The authors suggested that their lack of increased learning gains for the haptic condition may have been due to their scoring rubrics, which might not have adequately represented subtle changes that may have existed in students' understanding of the content.

There is also research showing a lack of beneficial effects for the use of haptics in the learning of physics. J. Park et al. (2010) investigated the effect of haptics in the classroom for learning point charges within nanotechology. By comparing assessments between groups receiving either visual and haptic or visual-only feedback, it was found that both groups benefitted equally and no statistical difference was found between the two conditions. Although the haptic group was found to be more motivated, enagaged, gained a more positive attitude to the task and were more confident, these effects did not translate into better test performance. However, the author suggested that a small sample size may have influenced the results and that further research was needed.

Another study which failed to find a positive effect of haptics on learning in physics is by Wiebe et al. (2009), who were investigating the use of cross-modal tactics to increase learning in the subject of levers. This study also provided both visual-only and visual-haptic contditions and used eye tracking technology to record visual attention in the task. It was found that although visual fixation time on key elements of the lever task was higher in the visual-haptic group, this did not translate to better learning as it was found that the visual-only group scored most highly in the embedded assesment. The authors suggest that cognitive load from using new techology to incorporate and coordinate haptic feedback may have had a negative effect on learning in this study but noted that the study was preliminary and that the results should be used with caution.

Also investigating the effects of haptics in the physical sciences was Young et al. (2011), who explored the effect of visual-only or visual-haptic feedback for the learning of buoyancy. Participants in this study were elementary school aged children, who were given an assessment before and after their learning activity to assess knowledge gain. Young et al. (2011) found that again, both the visual-only and haptic-visual groups benefitted from their intervention in learning the concepts of buoyancy, suggesting that haptic feedback could not provide significantly larger learning gains compared to visual-only methods. The authors suggested some limitations to their study however, including the limited nature of the ‘Falcon’ force-feedback device which may have affected the ability for students to benefit from the haptic information and the constitution of the learning assessment, which involved a large number of questions regarding visual, rather than haptic information, which may have inhibited the ability to detect changes in understanding.

There have been two prominent reviews concerning the literature of haptic feedback devices in science education. The first is by Minogue and Jones (2006), who reviewed 43 empirically-based peer-reviewed journal articles, three empirically-based books, 11 theoretically-based peer-reviewed articles and 31 theoretically-based books. The authors concluded from this research that many studies identified haptics as a positive addition to the classroom and therefore haptics can be described as “an exciting and innovative way to enhance the learning environment” (p.341). However, the authors do concede that there is some way to go to successfully integrate them into the classroom. Some specific uncertainties identified by the authors include whether using touch in instruction can either tap into or complement commonly neglected experiential, embodied, and tactile knowledge, and whether haptic technology is most suited to augmenting existing knowledge or the discovery of new knowledge. Addressing studies that found no learning gains after including haptic feedback, the authors concluded that when visual information is adequate for the task at hand, haptics may in fact be detrimental due to the dominance of visual over haptic information and subsequent increased cognitive load (discussed further in Section 2.4.4). Therefore, it may be possible that when visual information is not readily available (e.g. in micro or macro phenomena such as cells and forces) haptics may be more useful. Overall, Minogue and Jones (2006) concluded that there is potential in this area but there is more research needed to assess the full effect of haptic feedback and how to best implement it in education.

Subsequently, Zacharia (2015) conducted a systematic literature review of this topic using EBSCO databases, which have access to over 64,000 journals, 6 million books and 400,000 conference proceedings. After narrowing their search to those comparing virtual manipulatives with and without the provision of haptic feedback, 11 articles were included in the review. These articles yielded mixed results, with some publications providing evidence for a positive effect of haptics on learning and other (fewer) publications finding no benefits beyond that of visual-only feedback. Despite mixed results, Zacharia (2015) suggested that, due to the majority of studies finding positive results, that it may be reasonable to assume that haptic feedback has some effect on learning in science and especially on the learning of abstract concepts where visual information is inadequate. However, Zacharia (2015) cautioned that the relatively small number of empirical studies on this topic and small sample sizes prevalent in the present literature prevent any solid conclusions, warranting further research.

2.4.4 Cognitive load and using haptics in science education

As discussed in Section 2.4.2.2, the modality principle (Millar, 1999) suggests that different modalities are processed by their separate respective channels, and CLT (Sweller, 1994) suggests that the addition of haptics may aid learning of complex scientific concepts by utilising the haptic processing channel to lower cognitive load. However, there is evidence to suggest that using multiple senses in the form of an interactive, 3D haptic system in the learning of these complex topics may also provide difficulties. This section will outline the possible issues concerning the use of complex multi-modal systems in schools referring to CLT (Sweller, 1994).

Exploring CLT in more detail, Sweller (2011) identified three types of cognitive load: intrinsic, extraneous and germane. Intrinsic cognitive load is a ‘natural’ load imposed on the working memory by the inherent characteristics of the information and is related to the difficulty (denoted by the number of interactive elements) of the subject matter (Sweller & Chandler, 1994). This type of cognitive load is intrinsic to the learning goals and is separate from outside influences. Extraneous cognitive load however, is imposed by how information is presented, the instructional design, or the activities that are undertaken in the learning process. Extraneous cognitive load is unnecessary for the learning process as it does not directly contribute to the production of schema (Van Merriënboer & Sweller, 2005). Schema are cognitive constructs that allow the categorisation of information in the manner in which it will be used (Chi, Glaser, & Rees, 1982). Schemas are used for storage in long term memory and have a role in reducing cognitive load by allowing the integration of multiple elements of information into a single element (Mousavi, Low, & Sweller, 1995; Sweller, Van Merriënboer, & Paas, 1998). The construction of schemas allow learning by aiding the organisation and storage of information (P. A. Kirschner, 2002), and therefore extraneous load is not thought to contribute to the learning process as it is not necessary for schema acquisition. Germane cognitive load refers to the resources used and mental strain of dealing with the intrinsic cognitive load by constructing schemas and processing them into long term memory. Germane cognitive load is distinctive from intrinsic and extraneous load as it is not imposed by any learning materials, but can be more accurately described as a working memory resource that is allocated to the information relevant to learning (Sweller, Ayres, & Kalyuga, 2011). For learning to occur, germane load must be promoted (Ayres, 2006) which further distinguishes it from intrinsic and extraneous load. Germane load is likely to be affected by students' interest and motivation (Bandura, 1993; Leppink, 2010; Van Merriënboer & Sweller, 2005), as there is evidence that enjoyable or motivating activities can increase mental effort in learning (Um, Plass, Hayward, & Homer, 2012). Additionally, there is evidence that giving a learner control over a task's pace, sequencing, content, or presentation (such as in interactive computer-based learning environments) can increase germane cognitive load (Vandewaetere & Clarebout, 2013), potentially due to an increase in learner motivation (Paas, Tuovinen, Van Merriënboer, & Darabi, 2005).

It has been suggested that instructional designs that allow interaction, exploration, and the testing of hypotheses can increase germane load and therefore promote 'deep learning' (Moreno, Mayer, Spires, & Lester, 2001). Deep approaches to learning have been shown to be related to positive perceptions of the learning environment (Asikainen & Gijbels, 2017). 'Deep' approaches to learning have been described as prioritising meaning and critical thought over repetition of knowledge and have been suggested to be vital for successful learning in secondary education (Asikainen, 2014). Deep learning has been suggested to occur when students concentrate on the meaning or main message of the text rather than memorising it (Marton & Säljö, 1976), and describes the intention to understand and to engage in meaningful learning, focusing on main themes and principles (Asikainen & Gijbels, 2017). Therefore, the literature suggests that interaction and enjoyment during a learning task can foster the investment of germane load and therefore facilitate deeper learning.

Intrinsic, extraneous and germane loads are additive (Sweller, 2011), meaning that they all contribute to the cognitive load that is imposed on the working memory during learning and together have the potential to overload working memory capacity, inhibiting the learning process. The additive effects of intrinsic, extraneous, and germane cognitive load on learning have been demonstrated with the use of TEL in science classrooms. For example, animations are often thought to have the potential to aid learning of complex topics in science due to their motivating nature and ability to support the cognitive processing of dynamic subject matter (Lowe, 2004). However, the research has shown that animations often do not aid learning of complex concepts and in some cases are detrimental to cognitive processing (Ainsworth, 2008). It has been suggested that although animations can be entertaining and therefore motivating (Rieber, 1991), they require the processing of large amounts of information which changes quickly and requires students to hold previous frames in memory whilst simultaneously processing information being displayed (Lowe, 2004). Should an animation be demonstrating a complex concept, extraneous load from the presentation of animations coupled with the intrinsic load of the topic may exceed the learners ability to process the information (Lowe, 2001). It has been suggested that detrimental effects of animations on learning complex concepts may be due to overwhelming cognitive load from the difficulty of the topic and the complex presentation of information. (Ainsworth, 2008; Lowe, 2004).

As with animations, excess cognitive load also has the potential to affect the ability of haptic devices to aid the learning of complex, abstract content. For example, a haptic feedback device used to interact with a VR model involving complex concepts will have intrinsic cognitive load from the learning topic, but extraneous cognitive load can also be provided by combinations of unfamiliar elements, the use of a novel interface, high levels of interactivity, perceiving and integrating haptic feedback, the physical navigation of a VR 3D space and the processing of dynamic visualisations (Minogue et al., 2006; Sweller & Chandler, 1994; Wiebe et al., 2009).

As discussed in Section 2.4.2.2, The Additional Sensory Channel theory (Zacharia, 2015) would suggest that using an additional (haptic) sensory channel to process complex information may lower cognitive load and allow for more efficient processing. However, it has been suggested by Sweller (2011) that adding excessive complex information from an additional modality has the potential to overload working memory and diminish the positive effect of multi-sensory information. The overloading of working memory with additive cognitive load offers an explanation for some research finding no benefit for using haptics in learning. Zacharia (2015) found in their review that adding the haptic sensory channel does not always seem to help learning, and suggested that this could be because the haptic component may increase cognitive load rather than dilute it. Minogue et al. (2006) suggested that their failure to find significant learning gains using haptics may have been influenced by high cognitive load as a result of the high complexity of the subject matter, high numbers of components to be understood simultaneously and the novelty of both the information and the haptic interface. Wiebe et al. (2009) also did not find that the addition of haptics to visual information increased learning and suggested that the additional cognitive load in receiving and co-ordinating the haptic information may have affected the students' ability to learn.

The use of haptic information in the learning of complex science concepts has been discussed so far in the context of CLT (Sweller, 1994). However, despite robust presence in the research of memory and education, CLT (Sweller, 1994) is not universally accepted in the literature. A review of the open questions and conceptual considerations surrounding CLT (Sweller, 1994) was conducted by De Jong (2010), who consulted the 35 most frequently cited articles and highlighted current issues within the theory. For example, according to CLT (Sweller, 1994), intrinsic cognitive load is determined by the number of interacting elements and cannot be changed by instructional applications (Sweller, 1994; Sweller et al., 1998). However, there has been evidence to suggest that other factors may affect intrinsic cognitive load, such as prior knowledge of the task (Bannert, 2002; Schnotz & Kürschner, 2007) and a whole-part instructional approach (presenting materials in full complexity with all interacting elements, but using tasks that focus attention on certain subsets of interacting elements to increase the complexity incrementally) (Gerjets, Scheiter, & Catrambone, 2004; Van Merriënboer, Kester, & Paas, 2006). There is also evidence which calls into question the distinctness of extraneous and germane load, as instructional designs that create extraneous, redundant information (such as repetitions of the same information in different formats) may also require translation and abstraction between representations, which can be argued as a process of deep learning (discussed previously in Section 2.4.4) and therefore suggests the presence of germane load (Ainsworth, 2006). Research demonstrating techniques that may be able to reduce intrinsic load, or demonstrating a reduced distinction between extraneous and germane load suggest that certain conceptual assertations of CLT (Sweller, 1994) may not be accurate or should be revised to incorporate updated empirical evidence. De Jong (2010) also commented on the measurement of cognitive load, which currently does not distinguish between intrinsic, extraneous, and germane load and therefore obscures the multi-dimensional nature of the theory. Additionally, failure to distinguish between different types of load during measurement has often resulted in increased cognitive load being attributed to excess extraneous load without direct evidence. Consequently, the literature suggests that the relationships between each type of cognitive load remain unclear despite the wealth of research regarding the theory, and that further clarification is needed into how intrinsic, extraneous and germane cognitive load interact with each other and how they relate to the process of learning overall (Schnotz & Kürschner, 2007).

A fundamental criticism of CLT (Sweller, 1994) has been described by Gerjets, Scheiter, and Cierniak (2009), who suggested that the theory is constructed in a way which makes it difficult for research findings to confirm or falsify aspects of the conceptual framework. CLT (Sweller, 1994) includes germane load, which is seen as a 'positive' addition to the learning experience, but also intrinsic and extraneous load, which are seen to be potentially harmful. This dynamic therefore can result in findings related to the increase of learning being explained with increased germane load, and a lack or decrease in learning being explained by excess extraneous load. However, as individual types of cognitive load cannot yet be measured, the accuracy of these assertions cannot be confirmed.

Despite conceptual issues highlighted in the literature (De Jong, 2010; Schnotz & Kürschner, 2007), it has been suggested that, used as a framework, CLT (Sweller, 1994) can be fruitful for empirical research should the direct measurement of distinct cognitive loads be unnecessary (Schnotz & Kürschner, 2007). It has also been shown in the literature that the redesign of instruction based on the principles of CLT (Sweller, 1994) can result in better learning (Gerjets et al., 2009; Paas, Van Gog, & Sweller, 2010; Schnotz & Kürschner, 2007; Sweller & Chandler, 1994; Van Merriënboer et al., 2006). Therefore, although there has been discussion on the limitations of CLT (Sweller, 1994) in the literature, it has shown to be a valuable theory for the study of cognition and the presentation of multi-media information (Paas & Sweller, 2014).

2.4.4.1 Methods of lowering of cognitive load whilst using haptic systems

2.4.4.1.1 Activity design

The topics in cell biology identified as difficult to grasp in Section 2.1 understandably might provide high intrinsic cognitive load, but the research discussed here would suggest that extraneous cognitive load can be lowered by using an intuitive system of delivering information, allowing the benefits of the modality effect to occur. Additionally, if the activity is designed in a way that students enjoy and are motivated by, they may be more likely to invest in germane load for their learning (Section 2.4.4) (Van Merriënboer & Sweller, 2005).

2.4.4.1.2 Collaboration

An additional way to lower cognitive load on tasks involving complex information is collaboration. Research has indicated that collaboration between students is becoming a key feature of TEL (Hennessy, Deaney, & Ruthven, 2005) and it has been advised that the promotion of collaboration, dialogue between students and problem-solving should be considered for the most productive use of technology in the classroom (Hassler et al., 2016).

F. Kirschner, Paas, and Kirschner (2009a) suggest that multiple learners have the potential to expand their individual processing capacities during complex tasks by dividing the cognitive load between co-operating working memories. Evidence for this comes from studies showing that collaboration results in superior learning for complex subjects (F. Kirschner, Paas, & Kirschner, 2009b; Laughlin, Bonner, & Miner, 2002; Laughlin, Hatch, Silver, & Boh, 2006). F. Kirschner et al. (2009b) went further to discuss the concept of transaction costs in collaboration and their effect on learning. Transaction costs is the concept that completing the transfer of information between co-operating parties requires working memory resources, and that if this cost is too high it could diminish the effect of collaboration on lowering cognitive load. For complex subjects, the transaction costs would be relatively low compared to the possible learning gains, whereas in simple tasks, the transaction costs would outweigh the need for shared working memory. This is supported by evidence that although collaboration aids learning in complex subjects, for simple subjects, individual learning is advantageous (Andersson & Rönnberg, 1995; F. Kirschner et al., 2009b; Meudell, Hitch, & Kirby, 1992). Therefore, research suggests that collaboration on a complex and cognitively demanding task (such as those concerning difficult biological concepts discussed in Section 2.1) would be advantageous in allowing multiple working memories to spread cognitive load and aid learning.

There is evidence that teachers have a pivotable role in supporting collaboration through the focusing of tasks and the fostering of collaborative skills, such as explaining, justifying, negotiating and feeding back (Hennessy et al., 2005). In a classroom setting therefore, teacher-guided collaboration with TEL could be an effective tool for the lowering of cognitive load during complex tasks. However, empirical studies often require the absence of teacher guidance whilst testing educational interventions, including collaboration, and therefore any effects of collaboration on learning complex topics discovered with a lack of teacher guidance should be considered within this context.

2.4.5 Visual dominance

Sections 2.4.2.2 and 2.4.4 have discussed that, according to CLT (Sweller, 1994), using multiple modalities may be beneficial to learning complex concepts due to the splitting of cognitive load, allowing easier processing of the information. However, there is evidence that when presented with multiple modalities, the brain may not give equal weight to each sense. The visual sense has been shown to dominate other senses, an effect called 'visual dominance' (Posner et al., 1976). Several studies have demonstrated this effect. For example, a study by Rock and Victor (1964) presented participants with an object with incongruent tactile and visual shapes. After feeling and viewing the shape, participants were asked to reproduce their image of the object by either drawing it or selecting another object of the same shape. The authors found that the visual representation was dominant over the tactile representation, demonstrating the visual dominance effect which in some cases was present without the participant being aware of it. A well-known demonstration of visual dominance is seen in the effect known as 'the rubber hand illusion'. In this illusion, participants view a rubber hand being caressed at the same time as receiving an identically timed caress of their own hand. After a period of time, when participants were asked to pinpoint the location of their hand, they would choose the location of the rubber hand, therefore preferring the visual information being presented over the haptic information (Botvinick & Cohen, 1998; Farne, Pavani, Meneghello, & Ladavas, 2000). Dominance of visual information has also been shown in tasks involving memory. Posner (1967) found in their study, which involved a retention task including visual and proprioceptive information, found that when presented together, participants would behave as if only visual information was present. Additionally, Klein and Posner (1974) found in a series of experiments that if participants were told they needed to replicate visual information in a task, but both visual and proprioceptive information were presented, participants could ignore the proprioceptive information easily. However, if participants were told to remember the proprioceptive information, they did not seem to be able to ignore the visual information. These studies suggest that visual information dominates in memory tasks as well as perceptual tasks.

Two prominent hypotheses concerning visual dominance are the 'modality-appropriateness hypothesis' (Welch & Warren, 1980) and the 'directed-attention hypothesis' (Posner et al., 1976). The directed-attention hypothesis (Posner et al., 1976) states that a modality which receives directed-attention becomes dominant over others, creating a reduction in the availability of attention towards input from other modalities. Additionally, it is suggested that visual stimuli are typically paid more attention than other modalities (such as auditory or kinaesthetic) (Schifferstein, Otten, Thoolen, & Hekkert, 2010), contributing to a visual dominance effect. Therefore, when attention is directed to visual information for example, there is decreased attention to less attended sensory modalities (such as audio and touch). The role of attention in sensory dominance has been supported by studies finding that the tendency to ignore auditory information in the presence of visual stimuli can be influenced by guiding attention specifically towards the auditory modality (Colavita, 1974; Egeth & Sager, 1977; Sinnett, Spence, & Soto-Faraco, 2007). The modality-appropriateness hypothesis (Welch & Warren, 1980) suggests that when presented with incongruent information from visual and other sensory modalities, the sense which allows the greatest precision would be favoured. This hypothesis states that visual information is favoured because it is usually the most appropriate for the task (Pye, 2008). Additionally, it has been suggested that stimuli not immediately relevant for a task may not even be fully processed and therefore provide fewer distractions (Ward, McDonald, & Lin, 2000). Integrating the modality-appropriateness hypothesis with the directed-attention hypothesis, Welch and Warren (1980) suggested that modality dominance can be influenced by directed-attention, but attention is directed towards the modality most appropriate for the nature of the task (e.g. vision for spatial tasks) (Lukas, Philipp, & Koch, 2010). Evidence for the modality-appropriateness hypothesis (Welch & Warren, 1980) is shown in studies finding that for tasks involving spatial judgement, visual information is preferred as it is the most appropriate for the task (Bertelson & Radeau, 1981; Kitagawa & Ichihara, 2002). Additionally, as temporal acuity is greater for audition than vision (Welch, DutionHurt, & Warren, 1986), studies showing that auditory information is dominant for tasks involving temporal judgement (Fendrich & Corballis, 2001; Regan & Spekreijse, 1977; Shams, Kamitani, & Shimojo, 2000; Welch et al., 1986) also support the theory. For information where haptics may provide more accurate information than vision, the modality-appropriateness hypothesis (Welch & Warren, 1980) therefore suggests that haptics would be preferred. Furthermore, in circumstances when visual information is adequate, attention may not be attuned to haptic exploration due to its high processing cost, relative to its benefits (Klatzky, Lederman, & Matula, 1991).

Visual dominance has been suggested as a possible factor in studies exploring the use of haptics in science education. Some studies which have compared the use of haptics with visual information to haptics alone have commented on the possible interference of visual dominance. Wiebe et al. (2009) found in their study (discussed in Section 2.4.3) that participants in a visual and haptic group seemed to rely on the visual feedback as much as the haptic. The authors suggested that the information provided by the visuals (which may have been sufficient for the task) coupled with the high processing cost of the haptic information may have diminished the beneficial effects of the haptics. Discussing the results of their study concerning the use of haptics in learning biology, Minogue et al. (2006) also implicated visual dominance as a potential explanation for their finding that haptic activity did not enhance learning as expected. The authors suggested, that as students are usually presented information visually, the students may have focussed first on visual rather than haptic information during their tasks, which according to the directed-attention hypothesis (Posner et al., 1976) would lower the attention mechanisms available for the haptic sense. The modality-appropriateness hypothesis (Welch & Warren, 1980) and the directed-attention hypothesis (Posner et al., 1976) would suggest that using visual and haptic information for learning topics where visual information is not adequate may direct attention to the haptic sense. Therefore, designing a haptic activity in a topic which cannot be explored easily with vision alone (such as diffusion and concentration gradients) may be a suitable use of haptic information, facilitating the possible benefits of haptics described in Section 2.4.3.

2.4.6 Summary and conclusion

In summary, the literature has suggested that theoretical cognitive systems such as Embodied Cognition (Barsalou, 2008), DCT (Paivio, 1969) and CLT (Sweller, 1994) provide possible explanations as to why additional haptic feedback may positively impact the learning of complex scientific concepts. Research has found mixed results across several disciplines and levels of education (Minogue & Jones, 2006; Zacharia, 2015), with many finding positive effects of haptic feedback (Bivall et al., 2011; Brooks et al., 1990; Hallman et al., 2009; Jones et al., 2003; Jones, Minogue, Tretter, et al., 2006;

Minogue & Jones, 2009; Reiner, 1999; Schönborn et al., 2011), and others finding no additional gains beyond visual-only information (Bivall et al., 2007; Minogue et al., 2006; J. Park et al., 2010; Wiebe et al., 2009; Young et al., 2011). Literature reviews by Minogue and Jones (2006) and Zacharia (2015) both feature conflicting studies on whether haptics has a significant impact on learning. However, they both also suggest that haptics may be especially beneficial for abstract concepts where visual information is inadequate. Potential issues involving the combination of high intrinsic and extraneous cognitive loads with haptic systems presenting complex, novel information have been discussed, as well as how cognitive load may be alleviated by instructional design and collaboration (Section 2.4.4). The effect of visual dominance has also been identified as a potential barrier to the effective use of haptic VR systems in education. There is evidence that vision can often dominate other senses (Botvinick & Cohen, 1998; Farne et al., 2000; Klein & Posner, 1974; Posner et al., 1976; Rock & Victor, 1964), and that directing attention to haptic information and choosing a topic which is not adequately explored with vision may counteract this effect (Klatzky et al., 1991; Welch & Warren, 1980). Regardless, positive effects of haptics have been seen in a range of disciplines, including physical sciences requiring knowledge of abstract scientific concepts. Overall, this section showed that research suggests a positive direction for the use of haptics in science education, especially in learning involving abstract concepts where visual information is not readily available such as forces, biochemistry and cell biology (Zacharia, 2015). The research discussed in this section has also identified how cognitive load can be increased and decreased when using haptics, and that the use of an intuitive, enjoyable, collaborative, haptic VR system for exploring complex and abstract concepts may be advantageous to learning.

2.5 Literature review summary and conclusions

This literature review has discussed the difficulties associated with learning in science and particularly in cell biology (Section 2.1). Cell biology is abstract and complex in nature, with common misconceptions in topics of magnification/size and scale, randomness, and visualisation of cell structures. These misconceptions are thought to be due to the processing of abstract and cognitively demanding information, as well as the prevalence of inaccurate depictions of cells in educational material.

The abstract nature of the cell is thought to make visualisation of cell structures and processes difficult. As discussed in Section 2.3, visualisation is a sub-set of spatial ability, which is known to have a pivotal role in STEM learning and may even mediate gender disparities in STEM achievement. It was also discussed that 3D VR models may help students with the visualisation of cellular structure and processes, and the ability to switch between different modes of representation, both of which are important in developing understanding of the topic. The literature discussed in Section 2.2 suggested that spatial ability is an important variable for this topic, and it is thought that existing spatial ability could affect the ability for students to use and learn from a haptic system. Consequently, spatial ability was identified as a relevant factor to consider in this study, which is discussed further in Section 3.3.

Research in Section 2.1.3 discussing specific difficulties in learning cell biology had suggested the use of 3D virtual environments to improve conceptualisation of previously unobservable structures and processes, but also stated that haptic technology may be beneficial for presenting additional information without overloading students' cognitive resources. The benefits of using haptics in science education are discussed in Section 2.4.3, including theoretical support from Embodied Cognition (Section 2.4.2.1), DCT (Section 2.3.3) and CLT (Sections 2.4.2.2 and 2.4.4). DCT (Paivio, 1969) suggests that multiple modalities are processed by separate channels, and that presenting information via these multiple modalities is beneficial for learning. CLT (Sweller, 1994) also states that information is processed by separate sensory modalities, and that by splitting the processing of information across modalities, cognitive load can be decreased to the benefit of learning. According to these theories, including haptic information in the learning of cognitively demanding tasks, such as visualising cellular processes, could lower cognitive load and allow complex information to be processed more effectively. Reviews have also suggested that haptics may be especially beneficial for abstract concepts where visual information is inadequate, such as with cell biology (Dreyfus & Jungwirth, 1989; Zacharia, 2015). There has been cautionary research however, which suggests that in some cases, the addition of another modality may not be advantageous (Section 2.4.4). The additive effects of cognitive load were discussed including the intrinsic load from complex, abstract information, extraneous load from instructional activity design, and germane load from allocating working memory resources and constructing schemas. Methods of minimising cognitive load were identified, such as collaboration (Section 2.4.4.1.2) and designing an intuitive and enjoyable presentation of information (Section 2.4.4.1.1).

A review of the literature on the use of haptics in science education (Section 2.4.3) found mixed results, with many studies finding positive effects of using the haptic sense for learning and others finding no additional benefits. Reviews of the research topic were discussed (Minogue & Jones, 2006; Zacharia, 2015), which suggest that although findings are mixed, it is reasonable to assume that haptic feedback has some effect on learning in science, and there is potential in the development of haptics for this area, especially on the learning of abstract concepts where visual information is inadequate. Overall, the literature was found to support the use of a 3D, VR cell capable of providing haptic feedback to improve learning in cell biology, and this PhD aimed to explore whether such a system could increase learning gains in complex biological subjects.

3 Research Methodology, Design and Methods

3.1 Introduction

The previous chapter consisted of a literature review examining the various difficulties associated with learning cell biology. Visualisation and spatial ability were discussed as skills relevant to the understanding of these phenomena, and the potential use of haptics as an emerging technology to aid the understanding of difficult concepts was explored, including theoretical justification for why haptics may be useful for learning. To investigate the use of haptics to aid learning in cell biology, various approaches could have been adopted for this PhD. A pragmatic paradigm was chosen as the most appropriate for this research, and this chapter will begin by explaining the suitability of the chosen paradigm. This chapter will also briefly explain the rapid cyclical prototyping approach and development of the haptic system used in this research. An overview of each pilot study follows, which will document the methods and procedure for each pilot test, exploring the development and selection of psychometric tests and activities for use in the main study. Finally, the methods and procedure of the main study will be explained in detail.

Five pilot studies for testing and developing equipment and measures preceded the main study. The approaches used in the collection of this data were varied and included methods typical to various established research paradigms. The following paragraphs will explore the paradigms and methods chosen for this research, and why their choice for this study has allowed the most appropriate level of depth and accuracy in data collection and analysis.

3.2 Research Paradigm

3.2.1 Introduction

When engaging in research, certain assumptions are made in the endeavour to investigate phenomena. At the most basic levels, there are ontological assumptions (which concern the nature of reality and the nature of things) and epistemological assumptions (which concern the approaches to research and questioning the nature of reality) (Hitchcock & Hughes, 1995). Additionally, values and beliefs of researchers combine with ontological and epistemological assumptions to further impact the way research is conducted, causing research methods to be informed by how those investigating the world view and understand it (Cohen, Manion, & Morrison, 2017).

A paradigm has been described as the philosophical frameworks that outline assumptions about ethics, reality, knowledge and systematic enquiry (Mertens, 2012). More specifically, to the academic community a paradigm has also been described as the set of practices that define a scientific discipline in any particular time period, or a way of looking at or researching phenomena as an accepted model of working (Kuhn, 1962). Summarised, paradigms can be seen as a consensus on a set of principles and solutions in seeking knowledge which specify how phenomena are investigated (Cohen et al., 2017). Therefore, paradigms can be considered worldviews that reflect the beliefs and assumptions of the research community (Lincoln, Lynham, & Guba, 2011).

There are several paradigms relevant for educational research identified in the literature, although distinctions between these paradigms are not always clear or mutually exclusive. Pring (2015) suggested the existence of two paradigms. The first is of objective reality, which exists regardless of individual perception and relies on replicable and cumulative research. This paradigm is harmonious with the idea of quantitative research (Hammersley, 2012) which typically includes using hypothesis testing, numerical data and the control of variables to create generalised theories in which to organise the world. This view resonates with several paradigms described in the literature, such as prediction/positivism, post-positivism (Creswell, 2014) and empirical-analytic (Lukenchuk, 2012). The second paradigm described by Pring (2015) is of ideas and social construction, where researchers are thought of as an inalienable part of the research process, unable to be a separate observer. This view does not assert that there are objective truths of the world that are truly independent of the people who hold those beliefs, but that these truths are a subjective view constructed by people and society. This paradigm encompasses other paradigms such as constructionism (Creswell, 2014), understanding/interpretive and critical/theoretical approaches (Lather, 2004), and post-structuralist and transcendental approaches (Lukenchuk, 2012). Pring's second paradigm is also evocative of definitions of qualitative research provided by Hammersley (2012), who highlights the role of less structured data, detailed investigation of naturally occurring phenomena in lower numbers, subjectivity, and the use of verbal analysis in research (Cohen et al., 2017).

Pragmatism has been proposed as an additional research paradigm, which rather than focusing on the rigid choice of ontology, epistemology and axiology, selects methods of conducting research more practically according to the research question (Greene & Caracelli, 2003). Pragmatism is discussed further in Section 3.2.2, which discusses the philosophical underpinnings of the paradigm used in this research and the rationale for its selection.

3.2.2 Pragmatism as a research paradigm

As explained in Section 2.3.3, this research draws on Dual Coding (Paivio, 1969) and Cognitive Load (Sweller, 1994) theories, which suggest that there are distinct systems for different sensory modalities, which work together resulting in the beneficial effect of combined coding of sensory information. According to these theories, the use of the haptic sense in this study may lower cognitive load by utilising a separate processing channel, allowing an additional method of processing the complex information required in learning cell biology. Additionally, according to Embodied Cognition theory (Barsalou, 2008) haptic feedback could provide additional, unique, perceptual experiences in which to ground abstract concepts such as those in cell biology and aid learning. Consequently, the aim of the research was to explore the effects of using haptic feedback provided within a collaborative, 3D learning environment for the learning of cell biology, and the importance of certain psychomotor capabilities on how students use and learn from said feedback.

To explore this subject, the following research questions were developed:

1. Will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?

2. Does existing spatial ability have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?

3. Does existing fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment??

4. What design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?

Research Question 1 (RQ1) concerns whether using the haptic sense results in higher learning gains than just using visual stimuli, and Research Questions 2 (RQ2) and 3 (RQ3) concern whether the individual differences of spatial ability and fine dexterity affect the learning gains of students with or without haptics. These were assessed quantitively with the use of appropriate psychometric tests and a test of knowledge gain administered before, immediately after and 8 months after using the system. Research Question 4 (RQ4), however, is more exploratory. How students' learning may be supported or inhibited using a haptic VR system in the classroom has not been assessed in detail in the literature and so investigating students' learning and their perspectives on their learning may gain insight into this question by identifying design features that may have supported or not supported the learning process. RQ4 was assessed qualitatively using interviews, open coding, and thematic analysis. Considering the methods necessary to answer the research questions, a pragmatic, mixed methods approach was adopted.

This section will discuss the philosophical basis and development of pragmatism and mixed methods research (MMR), including the philosophical underpinnings and justification for the use of this paradigm for this research.

Researchers often use certain paradigms to represent the world view and beliefs used in their enquiries, framing, and guiding the way their research is collected and analysed. However, paradigms do not drive research, rather they frame the understanding of why a topic is investigated and clarify how it should be explored. Therefore, it is suggested that paradigms are not mutually exclusive (Cohen et al., 2017). A paradigm that embraces this view is pragmatism. Starting in the early nineteenth century, this movement was headed and developed by philosophers and researchers such as Charles Peirce, William James, John Dewey, George Herbert Mead and Arthur Bentley. Early pragmatism asserted that the traditional assumption that knowledge and truth can only be accessed by the use of one, objectivist scientific method was incorrect, and that in a pragmatic approach, enquiries should be aimed at refined and enriched experience (Maxcy, 2003). In modern research, pragmatism addresses the same assertion that knowledge can only be gained using a single method and adopts a ‘practice driven’ approach to investigating phenomena (Denscombe, 2008). This approach explains that ‘reality’ may be objective or subjective, and that to investigate ‘reality’, a practical, multi-solution, problem-centred approach must be used over the idea of a single type of accuracy (Lukenchuk, 2012). Subsequently, research is assessed by its ability to answer the questions set out by the researcher, rather than the particular type of research conducted (Feilzer, 2010). Pragmatism encourages the use of whatever methods work for answering the research aims and questions and asserts that ‘what works’ is the most suitable method of conducting research, regardless of the researchers’ philosophical leanings (Tashakkori & Teddlie, 2010). This allows researchers to not be beholden or restrained to a particular research method or technique in their pursuit of knowledge (Robson & McCartan, 2016) and allows the flexibility to utilise both quantitative and qualitative methods to improve the quality of the research (Onwuegbuzie & Leech, 2005).

The use of pragmatism has facilitated the rise of the use of mixed methods in research. Pragmatism has been described as the philosophical partner for the mixed methods approach (Denscombe, 2008) and provides a justification for using mixed methods approaches as an alternative to quantitative or qualitative research alone, should they be considered inadequate for delivering satisfactory results in isolation (R. B. Johnson, Onwuegbuzie, & Turner, 2007). MMR asserts that using one methodology or paradigm restricts how researchers can look at a problem, and therefore allows the use of both qualitative and quantitative methods to provide better understanding than either one in isolation (Creswell, 2011).

MMR can be defined as research combining various elements of quantitative and qualitative approaches including perspectives, data collection and analysis, as well as the inferences made from the research to give a richer and more reliable understanding of a phenomenon (Creswell, 2014). MMR includes several axiologies, research cultures and paradigms, but distinguishes that it is the research problem is central to this approach, where several different methodologies and perspectives may be needed for the most appropriate method of enquiry (Hesse-Biber & Johnson, 2013). As MMR also concerns the philosophical basis of research, including ways of viewing the world, including ontology, epistemology and axiology discussed earlier (Cohen et al., 2017), it has been suggested that MMR may in fact be a new research paradigm in of itself: a third research paradigm (Denscombe, 2008; R. B. Johnson & Onwuegbuzie, 2004; R. B.

Johnson et al., 2007). However, channelling the pragmatist approach, it is unnecessary to dwell on the specifics of paradigms and philosophical approaches and more appropriate to concentrate on 'what works' in context of the research.

In summary, 'what works' to answer the research questions in this study is MMR. The use of quantitative research allows the exploration of Research Questions 1-3 with the use of psychometric and knowledge-based tests, whereas the use of qualitative research allows the exploration of RQ4, with semi-structured interviews, open coding, and thematic analysis. The use of MMR in this case allows for a more comprehensive understanding of the research problem than any method in isolation. Pragmatism keeps the research problem central, and subsequently allows the use of MMR to do so. Quantitative measures are useful for this project to use standardised measures to accurately detect changes in knowledge scores and quantify aspects of spatial ability and fine dexterity in a way complimentary to statistical analysis. However, qualitative methods can detect more nuanced data, such as indicators of individual traits and views that may interact with learning and insight into participants' points of view, which can identify issues seen at the user level that may have been previously unnoticed. Without qualitative data, there is a lack of depth of the information available on how effective the system is for each student, and without quantitative data it is difficult to quantify or accurately measure certain variables and how they are affected. The combination of these methods with the pragmatic approach allows compensation between strengths and weaknesses of research strategies (Denscombe, 2008), allowing for more nuance and authenticism in researching the complexities of the problem (Day, Sammons, & Gu, 2008).

This section has explained the rationale for adopting a pragmatic, MMR approach. The next sections report on the methods used in collecting and analysing the data, including the development and selection of research instruments (Section 3.3), and methodology for the pilot studies (Section 3.3) and main study (Section 3.4).

3.3 Pilot Studies

3.3.1 Introduction

This thesis has discussed the rationales for developing the use of haptics for learning in science, and particularly cell biology in secondary education. The literature review (Chapter 2) has considered issues in understanding concepts in cell biology and how haptic feedback provided within a collaborative, 3D learning environment could support the learning of difficult concepts, drawing from DCT (Paivio, 1969), CLT (Sweller, 1994) and Embodied Cognition (Barsalou, 2008). To investigate whether haptic feedback provided within a collaborative, 3D learning environment could enhance learning, this project team aimed to develop a 3D learning environment with a stimulating visual and haptic interface. The previous section (3.2) described the rationale for using a pragmatic paradigm and MMR for this study and explained how this design is most suited to answering the research questions. To answer the research questions (Section 1.4), the project team adopted a rapid prototyping approach to develop the haptic device with formative evaluation using participatory research (Webb et al. 2016). To test and develop prototype haptic devices, test the implementation of psychometric tests (detailed in Section 3.3.3.2) and the testing procedure in a school environment, several pilot tests were conducted in our partner schools.

This section will document the pilot studies, including the development of the haptic system and activities, selection and administration of psychomotor/psychometric tests, the results and observations made during these studies and implications for the main data collection.

Preceding the main data collection, five pilot studies were conducted to develop and confirm the suitability of the design. Table 1 demonstrates the order of the pilot tests, their aims, and associated papers for more detail.

Table 1: Order of pilot studies preceding the main study, their aims, and associated papers.

Pilot Test	When pilot was conducted	Aims	Associated Papers
Pilot 1: Biology Undergraduates	April 2016	• Pilot a first prototype system with a small number of undergraduate biology students and to gather their feedback to help improve the system for further study.	Tokatli et al. (2016)
Pilot 2: A-Level students	June 2016	• Evaluate the suitability of the prototype system (adapted since Pilot 1) and identify areas of improvement for further studies. • To test the suitability of the chosen psychometric/motor tests and value of tests of student perceptions of their learning and of the system.	Webb et al. (2017)
Pilot 3: Manipulation study	December 2016	• Compare the manipulation performance of users with two different haptic interfaces: 3D touch and multi-fingered.	Tokatli et al. (2017)
Pilot 4: Younger Students	June 2017	• Continuation of Pilot 2 with a younger sample closer to the range expected for the main study. • Testing of a more developed haptic system, using multi-fingered haptics and a 3D cell membrane more appropriate for this age group. • Testing assessments refined from previous pilots and thought to be used in the main study.	N/A

		• Pilot a test of cell knowledge on cell membranes. • Collect feedback on the new haptic system and learning by using interviews to further improve the system for the main study	
Pilot 5: PGCE focus group	October 2017	• To allow student teachers a chance to use the haptic system and gather their views on the system and its impact on learning from a teaching point of view (via focus group). • Feedback on the system and the worksheet informed improvements for the main study.	N/A
		Main Data Collection **November 2017**	

The following section will describe the methodology of each pilot test, including the rationale for the choice of testing materials and how each pilot impacted the development of the project.

3.3.2 Pilot 1: Biology Undergraduates

3.3.2.1 Introduction

Preceding the first pilot test, meetings of the project team (including researchers and teachers from partner schools) were conducted to define what we would like to produce and how it should be presented to students. The curriculum relating to cell biology was agreed to have the most potential for positive gains, and Gaia Technologies provided existing 3D models, which were developed further throughout the project to become more complex and specific to our activity designs.

Pilot 1 in this project was qualitative and aimed to present a prototype 3D haptic VR activity to students and gather feedback on the activity, content, and usability of the system. The prototype system contained a plant cell simulation that allowed students to rotate, scale, dissect, construct, and observe cell processes. This section will describe the methods, equipment, and procedure of the experiment, as well as the results and their implications for further development of the system.

3.3.2.2 Method and procedure

3.3.2.2.1 Equipment

The haptic system for Pilot 1 was designed to facilitate collaborative learning by requiring two students to complete the activity, taking on the roles of ‘pilot’ and ‘navigator’. The pilot could interact with and manipulate the virtual world in VR, whilst the navigator could observe the world through a computer monitor, manipulate the scale of the virtual objects and switch between the phases of the task by using key commands. Both students experienced the role of pilot and navigator during the activity.

An Oculus Rift was used to allow students to view the 3D plant cell in VR, mounted on the desk for students to peer into as a 'virtual microscope'. The Oculus Rift is usually used as a head-mounted VR display, which provides low weight, high resolution displays, capable of delivering rich and immersive VR experiences (McGill, Boland, Murray-Smith, & Brewster, 2015). Head-mounted displays such as the Oculus Rift immerse users in a virtual world, but also separate users from people outside of the virtual world, presenting issues for communication and collaboration (L. Chan & Minamizawa, 2017; McGill et al., 2015). For this study, the Oculus Rift was mounted on the desk to limit potential barriers to communication between the students. A 'Phantom Touch 3D' robot was used, which allowed students to grasp and release cell structures and provide haptic feedback, and a computer monitor, and keyboard were used by the navigator to view the cell and interact with the program on a 2D screen. The Oculus Rift and Phantom Touch 3D devices were chosen by the bio-engineering researchers in the project group based on technological compatibility and suitability for the pilot activities. See Figure 3 for a photograph of two students interacting with the system and the equipment set-up.

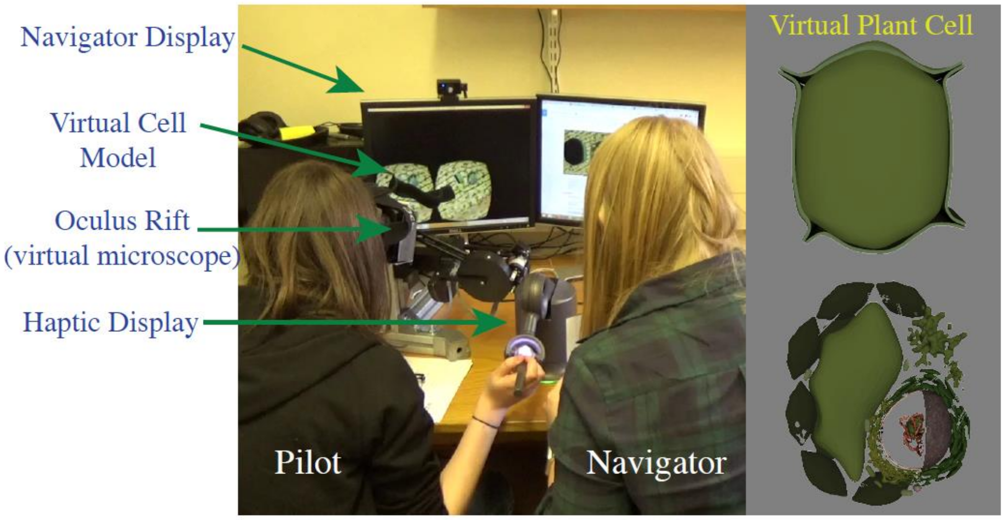


Figure 3: Photograph of students interacting with the cell and equipment set-up for Pilot 1.

3.3.2.2.2 Participants

Six undergraduate biology students (female, aged 19-22) were recruited by volunteer sampling. All but one participant had no experience with this type of technology.

3.3.2.2.3 Procedure

Ethical approval was granted by Reading University (Appendix B). After being provided information on the study (Appendix C) and giving consent (Appendix D), participants completed an activity on the haptic system whilst being video recorded and having notes taken by researchers during their interactions (Appendix E). The task consisted of three phases, during which the students were guided by a worksheet (Appendix F), developed collaboratively by the project group.

Phase 1:

- Students opened the program to see multiple cells. The students were able to interact with the multiple cells in the virtual world, which included touching them, rotating in the virtual world, and changing the viewpoint via the navigator controls.

Phase 2:

- The pilot selected a single cell from the multiples shown in Phase 1 and the navigator switched the virtual display to that of a single cell. Again, in this phase haptic interaction and exploration was encouraged.

Phase 3:

- Phase 3 was the most involved in terms of haptic navigation; the pilot located and selected the nucleus of the cell and the navigator switched the view to show this organelle in more detail. The students explored the layers of the nucleus of the plant cell and were instructed to find the ‘hidden DNA sequence’, which was done by the pilot and navigator orientating the view and changing the scale of the organelles.

The intended learning outcomes for this pilot test involved basic cell anatomy and a focus on the importance of the internal structures of the cell.

After the activity, the students were asked to fill out an online questionnaire (Appendix G) about their experiences, specifically the usability of the system and how the system may relate to their learning. Additionally, as interviews and discussions have the potential to highlight interesting perspectives (Ayers et al., 2007), an informal open interview was conducted with each pair of participants at the end of the session.

3.3.2.3 Results and discussion

Results of Pilot 1 came from observations during the task, video recordings and the questionnaire answers. Observationally, students were engaged in the task and took quickly to the navigation using the haptic system. The amount of collaboration varied between pairs of students, suggesting that collaboration may have need to be worked into the activity more consciously. Encouragingly, most students thought that the cells in the activity looked significantly different from textbook images, suggesting that the 3D VR perspective was useful in providing new perspectives to support their understanding of cell biology. According to the questionnaire, the overall usability of the system was rated between good and excellent, and students expressed that they thought using the system would support their learning.

The feedback from Pilot 1 suggested that an engaging prototype haptic VR system capable of supporting educational content had been successfully developed. However, from observing the students' interactions and comments on the system, some issues were noted to be addressed in the next cycle of development. Participants expressed wanting more realism in the model and commented that navigation in the 3D space was sometimes difficult. Moreover, the pilot sometimes expressed the wish to mount the Oculus Rift on their head and felt limited by having it mounted on the desk. As collaboration varied between pairs, incorporating more collaboration into the activity was identified as an aim for the next pilot test. Additionally, the cell model was of a plant cell and it was observed that some students expressed confusion over cell walls and membranes, which was counterproductive during the activity and risked misconceptions being formed. Difficulties with scale in the virtual world were discussed and it was thought that the dynamic nature of the cell was not presented well in the model, possibly reinforcing the common misconception that the cell was undynamic. How these issues are addressed in Pilot 2 is shown in Section 3.3.3.1.

3.3.3 Pilot 2: A-level students

3.3.3.1 Introduction

Pilot 1 (Section 3.3.2) trialled a prototype haptic device with undergraduate biology students, resulting in observations and feedback necessary for further development of the haptic system and educational activity. Feedback and observations were used to identify challenges in the design of the system and content, guiding changes to the system and activity for Pilot 2. Pilot 2 used a younger sample of participants (A-Level biology students) from two partner schools affiliated with this project and therefore was the first pilot to be conducted in a school setting. This section will discuss how the findings of Pilot 1 were addressed in Pilot 2, the rationale for the use of certain assessment techniques in this pilot, the selection of the psychomotor/metric tests, methods, results, and implications for further studies in this project.

3.3.3.1.1 Addressing findings from Pilot 1

As discussed in Section 3.3.2.3, issues and challenges from testing the first prototype system in Pilot 1 included those regarding the system (detail of the cell model, scale, navigating the space, viewing the cell) and educational activity (collaboration, risk of misconceptions on scale and the dynamic nature of the membrane). Following Pilot 1, a cycle of development commenced where industry partner Gaia Technologies built a new cell model, the design of the equipment was amended, and relevant assessments were researched and designed (Section 3.3.3.3). Issues and challenges from Pilot 1 and how they are addressed in Pilot 2 are described in detail in Webb et al. (2017) and are summarised in Table 2.

Table 2: Summary of design challenges in Pilot 1 and how they were addressed in Pilot 2 (Webb et al. 2017).

Design challenge from Pilot 1	How challenge was addressed in Pilot 2
Confusion between cell walls and membranes	Used an animal cell design rather than a plant cell.
The level of detail and realism in representation of the 3D model	Stylised, simplified 3D model provided by Gaia Technologies.
Viewing the 3D space	Oculus Rift mounted in stand as a “microscope” or on head allowing freer movement.

Enabling students to navigate the 3D space	Cell sized to make best use of the Oculus resolution. Haptic cursor changes size with depth to aid interaction with cell elements and navigation.
Navigating scale changes	Simple switching between different views but with no scale indications.
Opportunities for collaboration between students	Pilot and navigator with different views and functionality and tasks supported by a worksheet which asked them to discuss. Changing from 'pilot/navigator' to 'pilot/co-pilot' for half of participants to support equal engagement and responsibility.
Representing the dynamic nature of the membrane components	Not addressed in this study due to design challenges and early stage of development.

To address the challenges identified in Pilot 1, Pilot 2 was conducted using a participatory research approach with 28 students studying A-level science (12 girls, 16 boys). The aims of Pilot 2 included addressing the challenges identified in Pilot 1 to further develop the haptic system and content, and to test the implementation of assessment measures to the study to assess their usefulness and suitability.

After implementing design changes from the results of Pilot 1, an updated haptic system and activity was created for use in a school setting and with content suitable for the age and curriculum of the sample. In addition to trialling an improved prototype system, appropriate measures of psychometric and motor abilities were selected for this pilot, as well as measures of system usage and perceptions of learning. Pilot 2 therefore included an initial exploration of the tests and methods most suited to answering the research questions. Relevant measures used in the literature were gathered and piloted for their suitability to our sample and study procedure (the rationale for which is detailed in Section 3.3.3.2).

3.3.3.2 Rationale for the use of assessment techniques

The review of the literature (Chapter 2) identified possible variables that may affect how the student interacts with the haptic system. Firstly, the relationship shown between spatial ability and cell biology was identified as a possible variable to consider due to the haptic system requiring navigation of a 3D space and the manipulation of a 3D cell. It is possible that higher or lower spatial ability could affect how a student interacts with the 3D system. As discussed in Section 2.3.2, Hays' (1996) ability-as-compensator hypothesis would suggest that those with low spatial ability would benefit from graphical representations such as the 3D cell in this project, as they struggle to construct their own. Additionally, research has shown that interacting with 3D models has a positive impact on comprehension of 3D computer visualisations for those with lower spatial ability (Keehner et al. 2004). Conversely, Huk (2006) suggested that according to DCT (Paivio, 1969), 3D representation of a cell presents extra graphical information that may overload the visuo-spatial memory of those with low spatial ability, causing a detriment to learning (the ability-as-enhancer hypothesis). Consequently, spatial ability was decided to be an important aspect to measure in this project due to its potential ability to influence learning through the 3D haptic environment. Two separate spatial ability tests were utilised for the measurement of spatial ability, the details of which are discussed in Sections 3.3.3.3.3.1 and 3.3.3.3.3.2.

The haptic capability for Pilot 2 was provided by a Phantom Touch 3D robot, which includes a stylus-type control mechanism (Figure 10). This robot requires fine manipulation of the stylus to navigate and interact with the 3D space. Previous studies have identified a link between using stylus-based haptic robots and fine dexterity skills (Shahriari-Rad, 2014) and therefore it is possible that fine dexterity may influence the ability of a student to use the haptic device to navigate successfully. Consequently, it was decided by the project team that fine dexterity should be measured as a variable relevant to the study.

Furthermore, to measure gains in knowledge after the haptic activity, a short-answer question was devised by biologists at the University of Reading and science teachers at the partner schools as a pre and post-activity test of cell knowledge, tailored to the age of the sample and their curriculum. To evaluate the suitability of the prototype system and identify areas of improvement for further studies, it was also decided by the project team that measuring students' perceptions of the system would be useful for this pilot. To achieve this, measures of perceived learning, system usability and a semi-structured interview were included to gather a range of data.

3.3.3.3 Selection of psychomotor/psychometric assessment materials

In addition to testing the prototype haptic system, Pilot 2 also aimed to assess the suitability and usability of a range of materials that may be used in future work to measure relevant factors in this research. These materials include those used to measure dexterity and spatial ability and users' perceptions of the system. These materials and the justification for their selection for Pilot 2 will be discussed in the following sections.

3.3.3.3.1 System Usability Scale

For this project, it is possible that the usability of the haptic system may have an impact on the participants' ability to learn. For example, a low level of usability may cause participants to spend more learning time navigating the system, detracting attention from the biological aspects of the activity. Therefore, the project team decided that measuring the usability of the haptic system would be useful in future studies by offering insight into the effects of design on learning during development.

The literature is unclear on the superiority of one usability assessment method for VR or haptic systems. For example, Jia, Bhatti, Nahavandi, and Horan (2013) found in their paper exploring human performance measures for interactive haptic-audio-visual interfaces, that there were few empirical studies focusing on the usability and effectiveness of virtual training systems. They also explained that most existing virtual training systems are limited to visual and/or audio feedback, meaning any existing usability measures may not be suitable for assessing the efficacy of virtual training systems which include haptic feedback. Consequently, some studies focusing on haptic technologies in education have opted to use video recordings of discussions and interviews to assess the usability of their systems (Bivall et al., 2007) or created Likert scale questionnaires (Jones et al., 2003; Minogue et al., 2006; Reiner, 1999) (Reiner, 1999; Jones, Andre, Superfine & Taylor, 2003; Jones, Minogue, Oppewell, Cook & Broadwell, 2006; Bivall, Ainsworth & Tibell, 2007).

Although informal open interviews were included in Pilot 1, due to timetable constraints each interview was restricted to approximately 10 minutes and questions were often varied according to observations made during the task. Due to time constraints and the non-rigorous questioning style, I suggested that a faster measure which could be completed outside the classroom may be useful for Pilot 2. Likert scale questionnaires seen in the literature are usually designed especially for their respective systems rather than designed to be used across subjects, and so I sought to find an alternative, multi-discipline method of assessing usability. The literature revealed that many studies incorporating VR and haptic technologies in topics outside of education had used the 'System Usability Scale (SUS)' by Brooke (1996) (Bibin, Lécuyer, Burkhardt, Delbos, & Bonnet, 2008; Comai & Mazza, 2011; Gauldie, Wright, & Shillito, 2004; Kim & Sung, 2014; Lim et al., 2007; H. Richter, Ecker, Deisler, & Butz, 2010; Scali, Wright, & Shillito, 2003; Shillito, Scali, & Wright, 2003). This scale is a "quick and dirty" (Brooke, 1996, p. 33) ten item Likert scale questionnaire which allows the practitioner to quickly and accurately provide feedback on the usability of a system or product. This instrument is scored on a 5-point scale of strength of agreement, with final composite scores ranging from 0 to 100, where higher scores indicate better usability. Although the single number generated by the SUS is useful for relative judgments, a valid assessment of what the absolute numerical score means can be unclear. In industry, a ‘university grading analogue’ is commonly used, whereby the numerical scores are mapped onto a traditional grading scale (i.e., 90-100=*A*, 80-89=B, etc), the validity of which was supported by Bangor, Kortum, & Miller (2008), who found that the adjective rating scale complimented the SUS statements and score, and that the adjective ranges closely match those of the quartiles (see Figure 4).

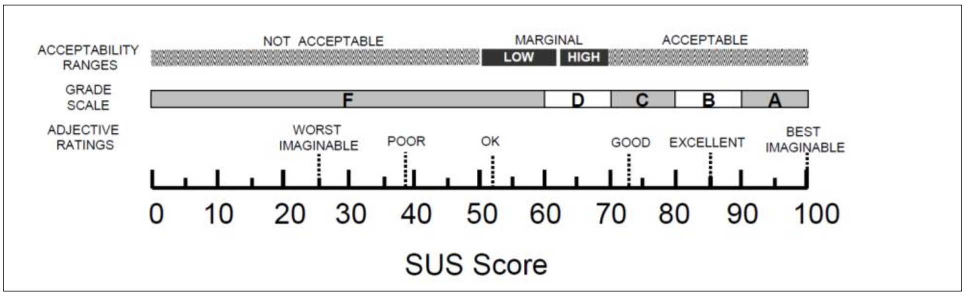


Figure 4: Grade rankings of SUS scores from Bangor, Kortum, and Miller (2009)

Due to its easy and quick administration, the SUS has become a widely used questionnaire for end-of-test subjective assessments of usability (Lewis, 2006). Furthermore, research has shown it to be robust and versatile, as shown by Bangor, Kortum, and Miller (2008) in their empirical evaluation of the scale, which used nearly ten years of research including 2,300 surveys and 200 studies on various systems throughout its development. The authors highlighted the versatility of the SUS due to it being “technologically agnostic” (pg. 574), allowing for it to be used on a range of systems and products, and allows a single score to be compiled that can be compared and understood by a range of disciplines. Research has found good estimates of reliability for the SUS (Bangor et al., 2008; Kirakowski, 1994) and the SUS has been found to correlate highly with more extensive measures used in industry, such as the SUMI and WAMMI (Sauro, 2011). Additionally, the SUS has also been found to be reliable for smaller samples of eight to 12 users (Tullis and Stetson, 2004), and is non-proprietary, allowing it to be accessed easily and making it cost effective.

In summary, these properties suggested that the SUS is a quick, reliable measure of usability, which could provide a score corresponding to the overall user-friendliness of a system. This score is easily described to multi-disciplinary project teams (such as in this research project) using a university analogue grading system. SUS scores had the potential to be helpful in this pilot to gauge an overall user-friendliness of the prototype system (which can be compared to future versions). The SUS however, is unable to provide information on specific points of improvement for prototype systems and so its usefulness was limited. To gather as much detail as possible for the prototype of this haptic system, the SUS (Appendix H) was included in the post-activity online questionnaire (Appendix I) to assist in the assessment of the prototype system and to inform on the suitability of the SUS for inclusion in the main study.

3.3.3.3.2 Morrisby Fine Dexterity Tweezer Test

The haptic device used in Pilots 1 and 2 was the Phantom Touch 3D haptic device, which uses a stylus to interact with a 3D virtual space. The Phantom Touch 3D necessitates some amount of hand dexterity, as the hand is required to rotate and manipulate objects in the 3D environment. There is some evidence that the use of a haptic device may be affected by fine dexterity. For example, one haptics-based research project that investigated the role of fine dexterity in using a system with similar navigation was the HapTEL project, which developed a 3D haptic system for use in dental education. Fine dexterity has been shown to be crucial in the success of dental skills, and therefore research within the HapTEL project determined the most appropriate and thorough measure of fine motor skills. After reviewing previous research and conducting pilot tests, the Morrisby Fine Dexterity Tweezer test was shown to be the most suitable and precise test of fine dexterity (Shahriari-Rad, 2014). Although fine dexterity may not be as crucial for the activities in Pilot 2 as for dental education, the ability to test whether fine dexterity is a factor in students' learning using the Phantom Touch 3D was useful, as it was expected that a more sophisticated haptic device would be developed for the main study, for which fine dexterity may have a larger impact.

The Morrisby Fine Dexterity Tweezer test (Figure 5) consists of a board of pins, metal washers, metal collars and a pair of tweezers. The original test had two parts: finger and tweezer tests. The finger test would require the participant to pick up a washer with their fingers, place it on a pin, then pick up another washer and place it on the same pin. The participant has 2 minutes to complete as many as possible. The tweezer test is identical but requires tweezers to complete the task. The test instructions allow adaptation of the task to suit research conditions, and as the tweezer grip was more evocative of the skills required for the Phantom Touch 3D haptic device used in this pilot, only the tweezer test was used.

Figure 5: Photograph of the Morrisby Fine Dexterity Test

3.3.3.3.3 Block Design Test and Spatial Relations Test

As discussed in the literature review (Section 2.2), research has shown that spatial ability is a necessary component for successful learning in science (Halpern, 2007, p. 125; Andersen, 2014). Cell biology especially presents the need for spatial ability in the form of visualisation due to the typical educational focus in this domain often being too small for a student to encounter in everyday life. Additionally, cell biology can often only provide exposure in the form of 2D microscopic images, requiring spatial skill for the learner to construct a 3D dimensional mental model of a true cell (Huk, 2006).

The 3D nature of the haptic environment in this study resulted in spatial ability being identified as a relevant variable to be measured in this project, as it is possible that a higher or lower spatial ability may affect how a student interacts with the system. A comprehensive investigation was led by Professor Tim Newton for the HapTEL project previously mentioned, which aimed to select the most suitable psychometric tests based on previous literature (Shahriari-Rad, 2014). This investigation identified two tests of spatial ability used frequently in the literature: The Spatial Relations Test (SRT; Levy & Levy, 1999) and the Wechsler Adult Intelligence Scale III (WAIS-III) Block Design Test (BDT) subset.

3.3.3.3.3.1 BDT

Due to the nature of the haptic system, this project required a test that would measure the visuo-spatial abilities and 3D/depth perception of the participants, which could indicate whether their learning was affected by their level of existing spatial ability. The BDT is a subset of the WAIS-III assessment used to measure these qualities (Shahriari-Rad, 2014; Soto & Kraper, 2013). This test requires students to replicate a 2D shape (presented on a card as a white and red pattern) using 3D blocks that have red, white, and half-red and half-white sides (Figure 2). Students' scores are calculated from ten patterns (5-14), which increase in difficulty. Students start with patterns five and six, which if they replicate successfully allows them to continue forward. Should the students not succeed perfectly on these patterns, patterns 1-4 are administered until two consecutive perfect scores are made. The patterns given should be replicated within a time frame. Patterns 1-4 have a time limit of 30 seconds, with patterns 5-9 allowing 60 seconds, and 10-14 allowing 120 seconds. The time taken by the student to replicate the pattern translates to a score which increases with faster completions (see Figure 6 for an example and Appendix J for the full scoresheet).

The BDT is a measure of visual-spatial and organizational processing abilities, but because it is a timed task it is also influenced by fine motor skills (Soto & Kraper, 2013), which have already been implicated as a relevant variable in this project (Section 3.3.3.3.2). An aspect of spatial ability that seems to be most pertinent to 3D models in cell biology is spatial visualisation (Huk, 2006; Vlaardingerbroek et al., 2014), which is involved in "visualizing shapes, rotation of objects, and how pieces of a puzzle would fit together" (Sternberg 1990, p. 93). The BDT is a characteristic test of spatial visualisation (Hegarty & Kozhevnikov, 1999) and is used widely in the literature (Shahriari-Rad, 2014). Consequently, the BDT was chosen to be piloted in Pilot 2 for future use within this project.

Design		Time Limit	Incorrect Design		Time (Sec.)	Correct Design ?		Score						
			Trial 1	Trial 2		(Please circle as appropriate)								
4		30"				Y	N	0	T2 1	T1 2				
5		60"				Y	N	0	T2 1	T1 2				
6		60"				Y	N	0	T2 1	T1 2				
10		120" (2:00 mins)				Y	N	0			36"-120" 4	26"-35" 5	21"-25" 6	1"-20" 7
	TOTAL SCORE IN EACH COLUMN													
	TOTAL RAW SCORE (MAXIMUM = 68)													

Figure 6: Example of the BDT scoring sheet

3.3.3.3.3.2 SRT

Further tests of spatial ability that were identified and used in the HapTEL project were spatial relations tests found in the ARCO book of Mechanical Aptitude and Spatial Relations Tests (Levy & Levy, 1999). The spatial relations tests are a series of paper-based tests typically used in mechanical aptitude exams designed to measure functions of spatial orientation, spatial visualisation, perceptual ability and visual-motor co-ordination (Levy & Levy, 1999).

The two tests identified by HapTEL researchers were the ‘Spatial Views’ (Figure 7) and ‘Solid Figure Turning’ tests (Figure 8). According to Levy and Levy (1999) the Spatial Views test measures functions of spatial orientation, whilst the Solid Figure Turning test measures functions of spatial visualisation. Barnea (2000, p. 308) referred to spatial orientation as the “the ability to imagine what a representation will look like from a different perspective” and has included it with spatial visualisation as complimentary skills associated with the ability to use visualisation to create effective mental models in science learning. Spatial Views has also been suggested to be capable of measuring spatial visualisation, which is often used for constructing 3D mental models from 2D images (Huang & Shyi, 1998). In the HapTEL project, (Shahriari-Rad, 2014) both Spatial Views and Solid Figure Turning tests were both initially used to measure spatial ability, but after pilot testing the Spatial Views test alone was deemed sufficient for their purpose. As the Spatial Views test has been used to measure spatial visualisation, I suggested based on the evidence, that the BDT in conjunction with the SRT (Spatial Views) would be capable of measuring these two visualisation skills. I therefore decided to trial these tests in Pilot 2 to assess their suitability for future use. The tests were administered on paper (Appendix K), and although they were administered previously by Shahriari-Rad (2014) with no time limit, a limit was necessary for this pilot due to student timetable constraints. 15 minutes was allotted for completion, which proved to be sufficient for students to complete the test.

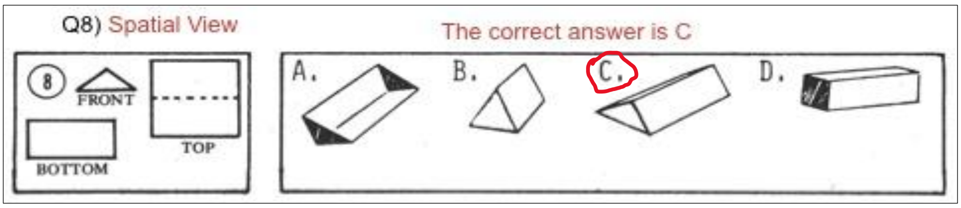


Figure 7: Example spatial views question from Levy and Levy (1999)

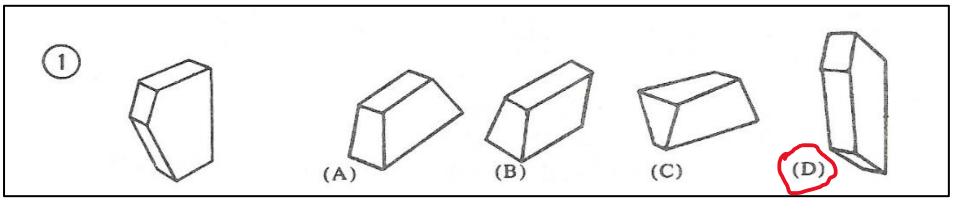


Figure 8: Example solid figure turning question from Levy and Levy (1999)

3.3.3.3.3.3 Pre and post-tests of cell knowledge

To answer RQ1, it was planned that an identical test of cell knowledge administered before, immediately after and 8 months after the use of the haptic system would be used to measure learning gains in the main study (Appendix L). However, for Pilot 2, most students had completed their exams and were no longer learning cell biology, and therefore the test of cell knowledge used in Pilot 2 was a revision exercise rather than one of learning. For the development of pre and post-tests for Pilot 2, biology teachers from both partner schools were consulted on their curriculum and the most appropriate content for the sample of A-level students. The project team agreed that protein synthesis was a suitable subject for the students in this pilot and the 3D haptic system was programmed by researchers at the Department of Bioengineering at the University of Reading to be used in an activity involving this topic.

The following short answer question was designed in consultation with the schools' biology teachers and was given a ten-minute time limit for completion: '*Discuss how organelles in a cell will work together to produce and position a sodium-potassium pump (protein) in the plasma membrane'.* This question was designed to allow for more detail than multiple choice questions and to gain a better view of the student's understanding of the processes rather than their ability to recite facts from their exam revision.

3.3.3.3.4 Learning Loss Scale

There is evidence that self-reports of perceived cognitive learning are a useful tool of determining learning gains in educational research. For example, Sitzman, Eli, Brown & Brewer (2010) conducted a meta-analysis to clarify the construct validity of self-assessments of knowledge in education and workplace training, and found that the relationship between self-assessment and cognitive learning was moderately strong. Additionally, Corrallo (1994) conducted a review of evidence for the validity of self-reported cognitive development and found moderate but reliable associations between self-reports and directly-measured cognitive skill levels.

The literature shows that several studies have used the Learning Loss Scale of perceived cognitive learning (Rovai, Wighting, Baker, & Grooms, 2009), which was first devised by Richmond, Gorham, and Mccroskey (1987). The Learning Loss Scale consists of two Likert items: the first asks students to estimate how much they learned in their course, and the second asks students to estimate how much they could have learned with the 'ideal' instructor. A final score is then calculated by taking away the score for the first item from the score for the second. The Learning Loss Scale has been shown to have a good test-retest reliability of .85 (McCroskey, Sallinen, Fayer, Richmond, & Barraclough, 1996) and has been shown by Chesebro and McCroskey (2000) to have a moderately strong concurrent validity in their comparison of self-report scores and standard exam scores. The Learning Loss Scale is also more time effective than other common perceived learning scales, such as the CAP Perceived Learning Scale (Rovai et al., 2009) and the Revised Learning Indicators Scale (Frymier & Houser, 1999). The literature therefore suggests that the Learning Loss Scale may be a useful additional tool to measure learning gains.

However, despite being reported as a reliable measure of perceived cognitive learning (Chesebro & McCroskey, 2000), there has been some disagreement on the usefulness of the Learning Loss Scale. The reliability scores reported by Chesebro and McCroskey (2000) have been criticised for lacking ecological validity (Hess & Smythe, 2001).

Additionally, Hooker and Denker (2014) reported in their replication of Chesebro and McCroskey (2000), that after minimising priming effects, a much smaller correlation was found between the Learning Loss Scale scores and performative cognitive learning measures, suggesting that the Learning Loss scale may not be suitable for cognitive learning assessment.

After considering the mixed evidence for the use of the Learning Loss Scale as a measure of cognitive learning, the scale was included in Pilot 2 to assess its usefulness for measuring learning gains for this project.

3.3.3.4 Methods and data collection

3.3.3.4.1 Haptic system and activity

The haptic system and activity were designed to allow interaction with a 3D virtual animal cell and its structures whilst facilitating collaboration and discussion between students.

Participants were given a familiarisation task before undergoing the haptic cell activity, which involved using the haptic system to arrange a pair of dice to match orientation, allowing the user to experience the range of motion, haptic sense and the head-mounted display (Figure 10). The familiarisation task took approximately five minutes.

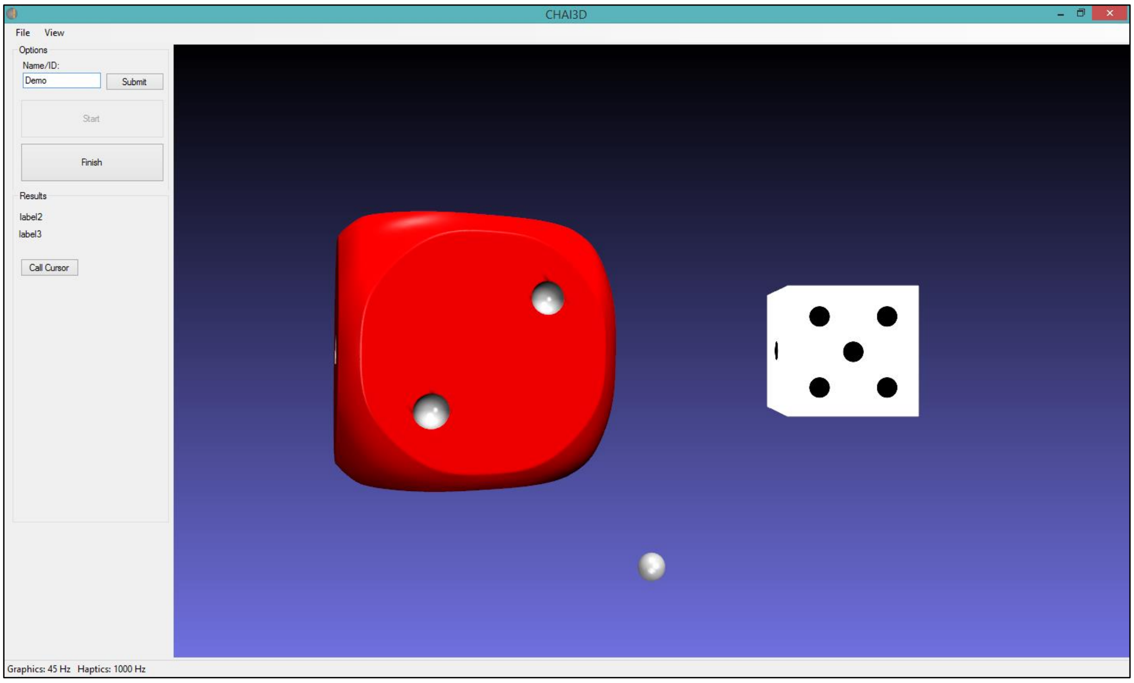


Figure 9: Dice orientation familiarisation task screenshot from Pilot 2

The system was designed for participants to work in pairs (a pilot and a navigator) to complete a task. The pilot was able to observe the virtual space through the Oculus Rift VR headset and interact with and manipulate the virtual environment through the haptic system. Within the virtual environment was a stylised, 3D animal cell, which aimed to show typical characteristics of the organelles. The cell was not realistically scaled as the aim was to display organelles in an easily identifiable manner, which in some cases required aspects to be enlarged in relation to others. Consequently, software developers for this prototype were not instructed in this early stage of development to use realistically scales items. The navigator could observe the space and cell through a computer screen, was able to control the scale of the cell and its components and rotate the view of the cell model. A Phantom Touch 3D robot (Figure 10) was used for the haptic interface, which had 3 actuated degrees of freedom with a 3 degree of freedom stylus. An Oculus Rift was used for the pilot display, which was mounted to the desk in front of the student as a 'virtual microscope' but was also able to be removed and mounted on the head. Virtual environment and haptic interactions were coded in Chai3D (version 3.1.1), which allowed easy integration of the hardware with the virtual world (Tokatli et al., 2016).

The activity was designed with the consultation of biology teachers from the project's partner schools and tailored to the knowledge and experience of the A-Level students in this sample. A paper-based worksheet was given to the pairs to guide their activity on the haptic system (Appendix M). The task involved taking the cell apart, identifying the organelles involved in protein synthesis, ordering them within the virtual space and recreating the cell to a 'functional' state. The pilot and navigator swapped roles half-way through the activity to ensure that all participants could experience the haptic system. This activity was video recorded with the participants' permission.

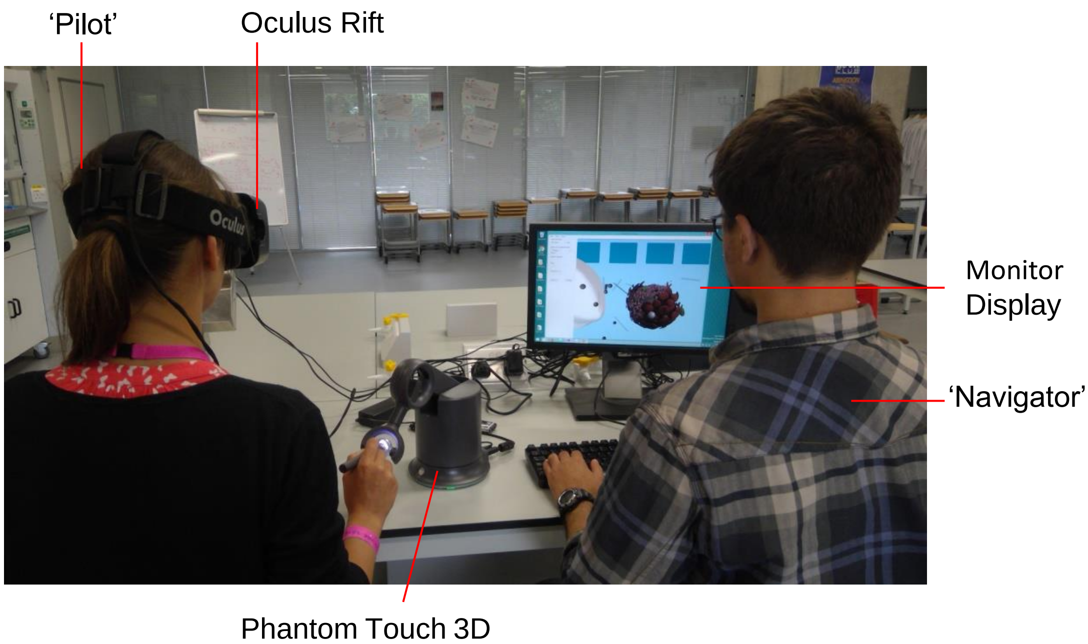


Figure 10: Set up of the system, featuring pilot, navigator and equipment (Webb et al., 2016).

3.3.3.4.2 Participants

Thirty A-Level students were recruited by volunteer sampling (14 female, 16 male) from two selective schools in partnership with this project. Participants were aged 16-18 years.

3.3.3.4.3 Procedure

Ethical approval was granted by KCL research ethics office (Appendix N). The study took place in school laboratories in each of the two schools. Information sheets, consent forms and the pre-activity cell knowledge test questions were completed as a group, whilst the remaining psychomotor/metric assessments were conducted individually. The assessments and order of administration are shown below.

1. Pre-activity cell knowledge test
2. Morrisby Fine Dexterity test
3. WAIS-III Block Design subtest
4. Spatial Relations Test
5. Haptic familiarisation task
6. Haptic cell activity

After the session was complete, students were given a link to complete a form containing the SUS, Learning Loss Scale and questions about their experience inspired by the NASA-TLX (designed to obtain workload estimates) (Hart, 2006) to complete in their own time. Similarly, due to the constraints of the school timetable, the post-activity knowledge test question was given to the school science teachers to administer and return to the researchers.

3.3.3.5 Results and discussion

This section so far has described the methods and procedure of Pilot 2. This was the first study in this project to assess the suitability of assessment materials for use in the main study, and the improved prototype haptic device and activity. This results/discussion section will outline the findings of Pilot 2 in relation to the assessment techniques, their suitability, and observational findings on the students' interactions with the system.

3.3.3.5.1 Assessment techniques: Implications for future study

This section will outline the findings of this study in relation to the assessment techniques, and what these findings mean in the wider context of the project and implications for the subsequent pilot studies.

3.3.3.5.1.1 SUS

The SUS data was compiled online, with each item included in a Google document that the participants were asked to complete in their own time. During the creation of the Google document however, I had excluded an SUS item (item 8) in error, which was not identified until after the data had been collected. Due to this error, the composite SUS score for the prototype could not be calculated from this pilot study, limiting its value.

Although information could be gained from the individual items in the scale, as the scale was originally designed to give a single reference score to measure a system's usability the author cautioned that individual items are not meaningful on their own (Brooke, 1996). Bangor et al. (2008) reiterated this caution in their analysis, which found correlations between all items as well as finding a single factor in their factor analysis of the items, suggesting that the composite score most reflects participants' views of overall usability. Consequently, although the SUS can give a single reference score for the overall usability of the system, it cannot identify areas on which to improve in the way that interviews, or observations may.

Another issue in carrying the SUS forward into the main study is that a small correlation had been found between SUS scores and age in a review of 203 studies by Bangor et al. (2008). The authors comment that the slope of the correlation was small however, and that further research is needed to assess definitively whether age has a significant impact on scores. Regardless, the main study participants are expected to be younger than those in this pilot, and although some studies involving children have used the SUS (Kim & Sung, 2014; Kobak et al., 2011; Naidu, 2005; Weiss, Gal, Eden, Zancanaro, & Telch, 2011; Weiss, Gal, Zancanaro, et al., 2011), this issue should be considered. After noting these issues and assessing the usefulness and practicality of using the SUS in the future, I decided that the SUS should not be carried forward in this project. This was because the information gathered from the SUS was limited in the context of this study and the proposed semi-structured interviews in future tests would yield richer and more useful data.

3.3.3.5.1.2 Fine Dexterity

The fine dexterity test was shown to be time effective and easy to administer and complete. It is a widely used test, measuring a variable that was thought may be a factor in how successful the haptic system would be in facilitating learning. One issue arises in that Morrisby recommends fine dexterity test for those aged 15 and over, which is slightly older than the proposed sample of the main study (12-13 years). However, percentile ranks were not required in this project and only the raw score was planned to be used as a covariate, which brought me to the conclusion that the administration of the fine dexterity test should not be an issue for the purposes of the main study. The test was administered successfully to A-level students in Pilot 2, but an additional pilot of the fine dexterity test administered to younger children can be seen in Section 3.3.5, which further determines its suitability. Overall, the piloting of this measure was successful and identified this test of fine dexterity to be a useful addition for future studies in this project.

3.3.3.5.1.3 BDT

The BDT proved slightly complicated to mark initially, but administration practice solved issues early on. Although the BDT ran smoothly in this pilot, administration requires one researcher and set of apparatus per student, making it the most time intensive measure of Pilot 2. However, due to the importance of spatial ability for learning in science (Section 2.2) and due to the BDT being a widely used test of spatial ability in the literature (Shahriari-Rad, 2014), it was a useful test to add to future studies to accurately measure this domain of spatial ability in future participants.

An issue with bringing the BDT forward to the main study however, was that it is a subset of the WAIS-III, which is designed for those over the age of 16 whilst participants in the main study were planned to be below this age. Those under the age of 16 would ordinarily use the Wechsler Intelligence Scale for Children (WISC), which is a more suitable option for the main study age group. After discussions with Psychologist Dr. Tim Newton (HapTEL Project) it was decided that the WISC would be a more accurate replacement in further studies.

3.3.3.5.1.4 SRT

The SRT was time effective and easy to administer. However, a potential issue arose concerning the range of scores collected. The maximum score of the SRT was 29, but the range of scores in this sample was small (22-28), and the mean score was high (M =25.62). It is possible that this test was too easy for this sample of high achieving A-level science students. The sample for the main study was planned to be younger, but also from the same selective schools, and so it was decided that modifying the SRT by adding extra items may be an improvement for future studies (addressed in Section 3.3.5.2). With amendments, this measure was thought to be a useful tool in the assessment of spatial ability of future cohorts.

3.3.3.5.1.5 Learning Loss Scale

The Learning Loss Scale was found to be time effective and easy to administer, as cited in the literature (Chesebro & McCroskey, 2000). However, some issues were identified in using this scale for further studies in this project. The Learning Loss Scale was designed for a study using undergraduate college students (Richmond et al., 1987), and the vast majority of studies that have used the scale have done so with a similar demographic. A lack of studies involving younger students means that the suitability of the Learning Loss Scale for proposed students in the main study is not clear, and it is possible that they may misunderstand the questions. Additionally, although the Learning Loss Scale has been used on studies involving 3D environments, this scale has not been used on educational haptic devices.

It was planned that the cell knowledge tests for the main study would involve multiple question formats for more in-depth data, which is preferable in the measurement of learning gains for this study. Additionally, semi-structured interviews planned for the main study would be able to provide a more detailed account of students' perceived learning. The use of more in-depth measures of learning in the main study therefore made the Learning Loss Scale superfluous, and considering doubts on reliability and validity (discussed previously in Section 3.3.3.3.4), I made the decision to not include the Learning Loss Scale in further studies.

3.3.3.5.1.6 Pre and post cell knowledge question

This pre and post cell knowledge question was designed specifically for the pilot sample and to fit the capabilities of the prototype haptic system. Having recently covered cell biology in their exams, these questions acted as a revision exercise rather than a learning experience as the activity for main study would be. In addition, the capabilities of the haptic system would change for the main study, including a new model on a separate cell biology topic. Therefore, the content of the pre/post cell knowledge question in this pilot was not taken forward for future studies.

As mentioned in Section 3.3.3.4.3, due to time constraint the post-test question was administered without the presence of researchers. An issue arose in one school, where very few post question answers were returned, possibly due to confusion on answering the same question pre-activity. It was also shown that question answers varied widely depending on the student, providing an inconsistent amount of detail. Due to this, pre/post cell knowledge question analysis was unfruitful. After encountering these difficulties, I decided that the post-test question should be administered by the researchers in further studies, providing supervision of the assessment and a lower chance of administration error or confusion. To compensate for varying detail provided by students in their answers, it was planned that knowledge tests in further studies would provide a mixture of multiple choice and short answer questions to provide more detailed data. Going forward, alternative assessment designs to measure knowledge gain were considered, with the consultation of biology teachers, to tailor for the main study sample. However, the exact nature of the questions could only be finalised once the final haptic activity was created.

3.3.3.5.1.7 Interaction with the haptic system and insights into design

The project team used observations of participants, informal open interview answers and the Google feedback form to gather insight into the participants' perceptions of the haptic system and activity. Key points are discussed in this section to draw conclusions for use in further studies, and detailed information on Pilot 2 can be found in Webb et al. (2016).

All students expressed that they enjoyed receiving touch feedback from the haptic system. However, there were comments on the limitations of using this device in the cell activity due to the lack of texture, as participants had experienced texture in the dice familiarisation game. This deficit was due to the prototypical nature of this version of this system, and texture associated with different organelles and their characteristics was planned to be implemented in future programming.

By observing the students using the haptic system, limitations were found in the navigation of the 3D space. It was found that participants often used the haptic sense to find their way around the model, but occasionally lost the cursor, often by getting ‘stuck’ in parts of the cell which were not visible.

Perceptions of the Oculus Rift were varied among participants. It was found that rather than using the table mounted ‘microscope’ method, most participants preferred to use the fully head-mounted display. However, there were some issues with students being able to view the entirety of the cell model easily with this display and so perceptions of its usefulness were varied. Overall, there were some issues found in using the Oculus Rift to view the model, but the immersive nature of the display demonstrates value to this type of system as was evidenced by the students’ preference for full immersion over desk-mounted display. Some participants also commented that they found the resolution of the Oculus to be poorer than expected. However, Oculus Rift technology is continuously improving and a new version with a higher resolution was available further on in the development of the system.

The use of the Oculus may have also impacted collaboration between participants. In the desk-mounted position, collaboration was facilitated, allowing the pilot to lift their head away from the virtual space to communicate with their navigator and see the navigator’s view of the cell on the monitor. However, with the head-mounted display this proved more difficult as the pilot could not turn to see their partner or view the monitor. As this activity aimed to involve collaboration between students, this issue was considered in future studies so that communication and collaboration could be facilitated by other means (e.g. through the worksheet instructions and questions). The use of the Oculus Rift over other technologies was debated, but hardware and software compatibility and key educational considerations lead the bio-engineering team in this project to favour the Oculus over alternative 3D systems such as the HTC VIVE. With the continued development of the 3D model and software, the Oculus Rift was expected to be a suitable choice for use in future systems.

The pairs of students generally worked well together and discussed their task effectively. An alteration to the worksheet instructions was made early on, changing the term ‘navigator’ to ‘co-pilot’, as it was found that the previous label encouraged ‘navigators’ to mainly give directions to the pilot, which would often not correspond due to the difference in the students’ views (Oculus versus monitor). This alteration seemed to remedy that problem, encouraging the co-pilot to take on the tasks of rotating the view, changing scale, and relaying task directions on the request of the pilot.

The task was successful in fostering communication between the students, however, the rebuilding of the cell at the end of the activity (where organelles were placed relating to their function) was often completed by memory rather than reasoning. This suggests that part of the task did not encourage much understanding or connecting of structure and function. For this reason, it was decided that the reconstruction of a previously whole structure should not be carried forward as a task in further studies.

In relation to popular misconceptions in cell biology, participants noted that components of the cell were coloured for simplicity and they used these colours in the identification of the organelles, despite most students commenting that this is unrealistic. Some students however, commented that they thought duller colours used in the cell model (e.g. brown) may have been realistic because it was different to what is typically found in textbooks. It was discussed by the project group that although the aim was to create more ‘realistic’ representations, presenting the molecules in colours usually depicted in textbooks may be less harmful, as a model cannot realistically depict the translucent reality of molecules, and although students seem to be aware bright colours are unrealistic, it is not as clear whether they identify duller colours as unrealistic. Therefore, altering of the cell model in was discussed, including the use of more standard colours in future models to avoid misconceptions. Developments in the colours used in the model are discussed in Section 3.3.5.2.1.

Some issues concerning the understanding of scale between organelles were also encountered. For example, some students were unsure on whether a component of the cell was a ribosome or a lysosome (one of which is much larger than the other). This corresponds with the literature which identifies scale as commonly misunderstood in cell biology (Section 2.1.2.1.1). As explained previously, the model cell in this pilot was scaled incorrectly for simplicity, however, due to the common misconceptions around this topic highlighted in the literature review (Section 2.1.2.1.1), future cell models in this project were designed to be more realistic in their comparative dimensions. Realism in the model cell was improved in future studies by adding details complimentary to using the haptic sense. For example, an important concept to understand concerning the cell membrane is the diffusion gradient, which is not easily demonstrated with visual information alone. By using subject material such as the cell membrane with the addition of the haptic sense in future studies, characteristics which are intrinsically linked to the function of the cell but are difficult to convey visually can be demonstrated with multiple modalities.

3.3.3.5.1.8 Conclusions

This section has discussed Pilot 2, which aimed to test an improved haptic system and activity in a school setting. Pilot 2 also aimed to test measures of system usability, student perceptions, spatial ability, and fine dexterity to assess their usefulness and appropriateness for further studies.

The selection and administration of the psychometric tests chosen for this study was discussed with reference to previous research, as well as the implications of these results for their use in further studies. Pilot 2 confirmed the value of some tests (Morrisby Fine

Dexterity, BDT, SRT) and identified others as unsuitable for future study aims (Learning Loss Scale, SUS, the post-activity cell knowledge test question). However, further pilot studies would involve younger students and therefore the appropriateness of certain tests designed for older samples (such as the WAIS-III version of the BDT) must be considered.

Concerning the haptic software and model cell, this pilot was successful in creating an interactive, 3D virtual system with a task which facilitated discussion amongst peers. However, the prototypical nature of the system in this pilot presented limitations, including scaling and navigation. The advantages and disadvantages for the method of viewing the VR model would also be deliberated in the next cycle of development (Section 3.3.5.2.1). In this next stage, the aim was to create a more realistically scaled and haptically stimulating model, appropriate for a younger sample and their curriculum, which could be integrated into a classroom setting. The findings of Pilot 2 were used to improve the haptic system, psychometric tests and methods for future pilot tests and ultimately, the main study (Sections 3.3.5.2.1, 3.3.6.1.1 and 3.4.2). Pilot 3 (Section 3.3.4) planned to explore the most suitable method of haptic manipulation for the main study and discusses the use of multi-fingered manipulation compared to the stylus-based method seen in previous studies.

3.3.4 Pilot 3: Manipulation study

3.3.4.1 Introduction

Considering the development of the VR haptic environment, a vital component was the haptic robot which allowed navigation within the VR world. For Pilot’s 1 and 2, the Phantom Touch 3D haptic robot was used, which is a single-contact haptic interface which allows the navigation and manipulation of a VR space with a single cursor. To manipulate objects in the virtual space with the Phantom Touch 3D device, the user must touch the virtual object with the cursor and press a button on the stylus of the device. However, as described in Section 3.3.3.5.1.7, there were some limitations to the use of this device. Participants sometimes had difficulty in locating the single cursor, getting stuck whilst rotating objects, or in-between organelles that were not visible to them.

The developers of the haptic environment at the University of Reading suspected that a different device may offer a more intuitive method of navigating the 3D space, and therefore address some of the navigation issues seen in Pilot 2. It has been suggested that multi-fingered haptics may be a valuable tool for immersive VR experiences and dextrous manipulation within VR environments (Lee et al., 2019). Therefore, a multi-fingered haptic device was developed to compare the suitability of multi-fingered haptics for the main study in comparison to the stylus-based methods used previously. A multi-fingered device was developed based on two Phantom haptic interfaces, where each device is attached to the user’s thumb and index fingers requiring the user to make a pinching motion to grasp and manipulate objects (Figure 11).

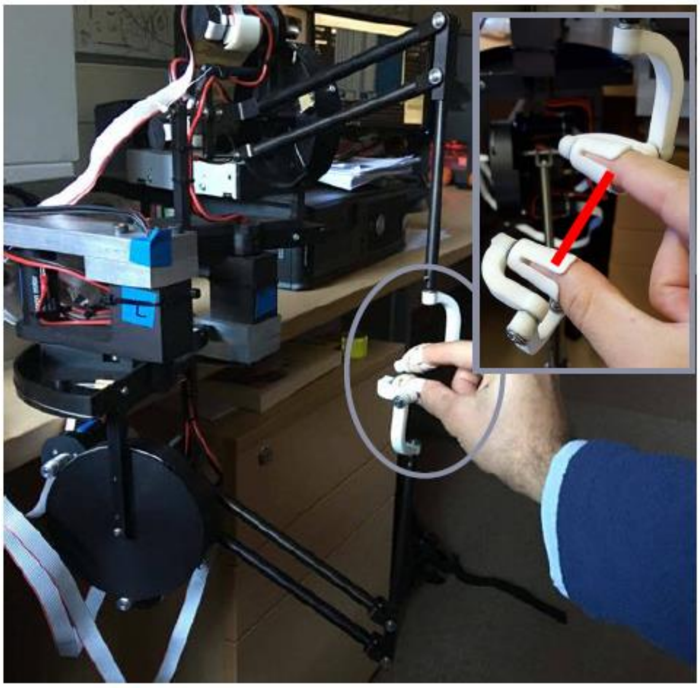


Figure 11: Multi-fingered haptic interface (Tokatli et al., 2017)

To compare the performance of the single finger and multi-finger interfaces, an experiment was conducted to investigate the performance difference between the devices in terms of speed, accuracy, and task load on a 3D rotation task. Pilot 3 also presented an opportunity to further test the administration of the BDT, SRT and fine dexterity tests. This section will outline the experimental design, task and conclusions of this comparison, and a more detailed account can be found in Tokatli et al. (2017).

3.3.4.2 Experimental design

For this experiment, a virtual environment was developed with CHAI3D software, which showed two dice in a virtual space (Figure 12), viewed through a 2D computer monitor. The goal of the task was for the participant to match the orientation of one die with the other by using the haptic interfaces as accurately and quickly as possible.

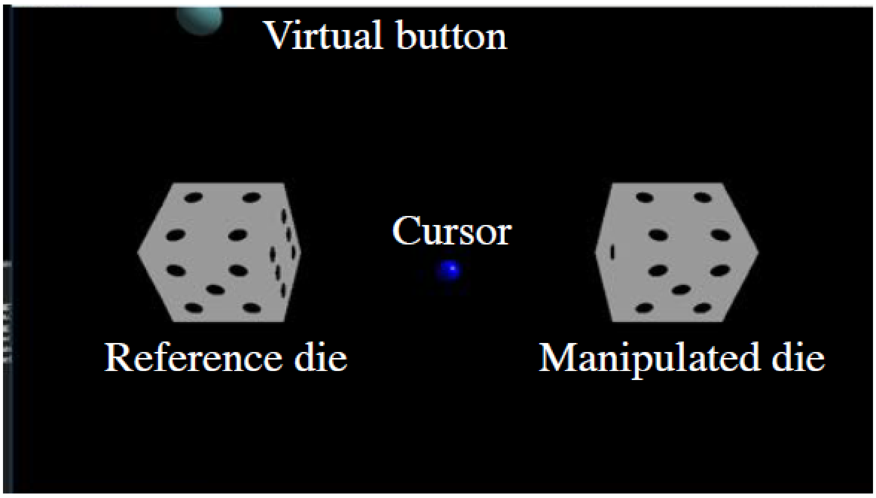


Figure 12: Dice task used in the manipulation experiment (Tokatli et al., 2017)

The design was repeated measures with all participants using the single finger and multi-finger device. The order of presentation of the haptic devices was also counterbalanced. The task consisted of two phases: phase 1 compared single and multi-fingered interaction, and phase 2 compared multi-fingered manipulation with and without haptic feedback. In addition to the haptic interface factor, there were also factors of rotation angle (with 10, 70 and 130 degrees) and principal axes of rotation (1 or 2 axes).

3.3.4.3 Participants

This study was granted ethical approval by the University of Reading School of Biological Sciences. The sample consisted of 10 participants (4 female, 6 male) recruited by volunteer sampling, aged 19-37 (mean age 27). Every participant completed phase 1 (trials with the single finger and multi finger interfaces), and 8 participants went on to complete phase 2 (multi finger interface with and without haptic feedback).

3.3.4.4 Procedure

Before engaging in the task, participants engaged in training rounds to familiarise themselves with the equipment and instructions. Once it was clear they understood the task and how to use the equipment, participants started the task by clicking a button on the screen. The participants then completed the trails, orientating the manipulated die to match the reference die. The order of the trials was randomised, and participants completed 12 trials with different configurations of the reference die.

After completing the task, participants were asked to complete a questionnaire which was based on the NASA Task Load Index (Hart & Staveland, 1988), which is a subjective assessment tool that measures the effectiveness or performance of a task. After completing the questionnaire participants were given the choice of completing phase 2.

After completing the haptic tasks, participants were administered the BDT, SRT and fine dexterity tests in the same method explained in Pilot 2 (3.3.3.3). However, early in the testing procedure the fine dexterity test was no longer administered due to damaged test equipment.

For analysis, a research colleague conducted a 3-way repeated measures ANOVA for each phase including the number of contacts, completion time and orientation errors. Additionally, paired t-tests were used for NASA-TLX scores for each phase.

3.3.4.5 Results and discussion

Analysis shows that single-and multi-contact haptic interactions had similar completion times ($F(1, 9)=0.16$, $p=0.70$), but a significantly different number of contacts per rotation ($F(1, 9)=69.27$, $p < 0.001$). This suggests that manipulation with the multi-finger haptic system was more agile. Additionally, no significant difference was found between the haptic interfaces in terms of the orientation errors.

The NASA TLX scores showed that participants preferred the multi-finger haptic interaction over the single finger interface, rating it as having a lower subjective workload ($t(7)=2.86$, $p=0.02$). This could be explained by the intuitive nature of this method of haptic interaction, as haptic feedback is provided to both the thumb and index fingers (Tokatli et al., 2017).

Observationally, participants adapted well to the multi-finger haptic interface and seemed to intuitively manipulate using this interface. For the single-contact haptic interface however, it seemed to take more time and the movements were less intuitive.

With haptic versus non-haptic feedback in phase 2 of the task, the haptic feedback was shown to improve completion, and the haptic force made it easier for participants to hold and release the virtual object. Therefore, haptic feedback was shown to improve the agility of the haptic interface in this case.

In conclusion, the multi-finger interface had a smaller rotational workspace and participants were required to make a higher number of contact-release motions than with the single finger interface. However, participants still achieved the same level of orientation accuracy and completion time with both devices. Additionally, the questionnaire showed that participants rated the multi-finger interface as having a lower subjective workload. Haptic feedback in the multi-finger system also appeared to provide benefits over no haptic feedback in terms of completion times and subjective workload, but not on orientation error or the number of contact-release motions. With the stated preference for the multi-fingered interface, increased agility, and lack of significant difference in completion time, the findings of Pilot 3 suggested that a multi-finger interface was more appropriate for the haptic environment, and therefore was planned to be implemented in further studies in this project.

3.3.5 Pilot 4: Younger students

3.3.5.1 Introduction

Despite promising results from Pilots 1 and 2, the proposed sample for the main study were of a younger age than those previously tested. Science teachers from the project's partner schools were consulted on their curriculum and at which age students would cover topics particularly difficult to grasp in cell biology (Section 2.1), which identified a key period at the end of year 8 (ages 13/14). Participants in Pilots 1 and 2 were either biology undergraduates or A-Level students of ages 18 and over, and so a subsequent qualitative pilot study (Pilot 4) was conducted with an improved system and cell model and an activity/worksheet to match the age and ability levels of the proposed age of the main study participants. This section will describe the development of the system using the results from Pilots 2 and 3, how challenges identified in those studies were addressed, the methods and procedure, and the results and their implications for the main study.

3.3.5.2 Design and methods

3.3.5.2.1 Development and addressing challenges from Pilots 2 and 3

After evaluating the feedback and findings from Pilots 2 and 3, the next cycle of development began for the haptic system to suit the needs of the proposed main sample. From the previous pilots, technical and educational challenges were identified for the next cycle of testing which are summarised in Table 3.

Table 3: Challenges from Pilots 2 and 3 and how they were addressed in Pilot 4

Challenges	How they are addressed in Pilot 4
Requests for more haptic interaction with the cell	Cell membrane model was developed, utilising the haptic sense.
Requests for more realism	Improved cell model with more attention given to scale, structure and the number and speed of molecules.
Near ceiling scores using the SRT	Added section to the SRT measuring spatial relations more broadly.
WASI III BDT designed for adults	Alternative BDT found suitable for children but was unable to be sourced in time for this pilot.
Concerns over differences in how researchers interact with students	Common protocol developed for researchers to follow in interactions.
Difficulties navigating the 3D space	Multi-fingered systems used as trialled in Pilot 3.
Poor return rates of post-test when administered by teachers.	Post-test administered by researchers for supervision.
Representing the dynamic nature of the membrane components	With a cell membrane model including the movement of particles, the dynamic nature of aspects of the membrane is represented.
Possible misconceptions with the use of non-standard ‘dull’ colours	Use of standard colours for molecules.
Limited cell knowledge test suited to A-Level students	Cell knowledge test designed around new activity with a mixture of question types.

Using the results from Pilot 2, the cell model was improved to better reflect the learning needs of the students. With consultation from science teachers at the schools and biologists at the University of Reading, it was agreed that the age of the proposed main study participants, diffusion of particles across the cell membrane and the nature of the membrane are particularly difficult subjects to grasp (as discussed in Section 2.1). Additionally, using a model of the cell membrane allowed further utilisation of haptics, as the diffusion gradient is difficult to learn by visual-only methods and is therefore complimentary to the haptic sense. A diffusion gradient can be felt but, it is hard to present the same information visually. Therefore, for this pilot a new cell model was designed as a section of cell membrane (Figure 13).

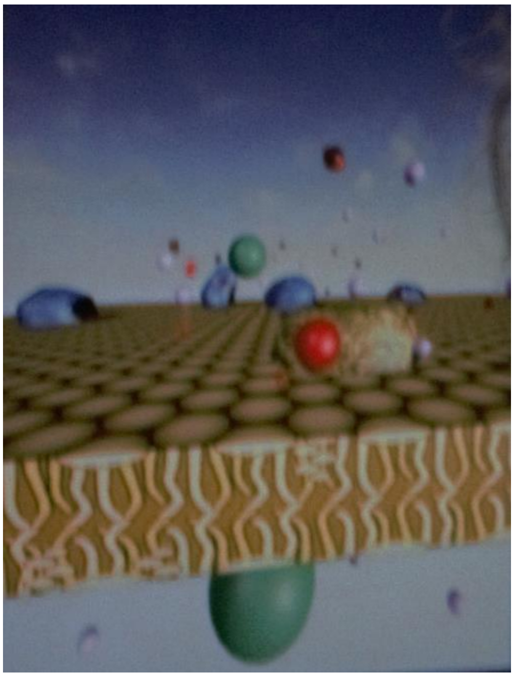


Figure 13: Screenshot of model used in Pilot 4

The design of the model was in depth. Biologists, and our industry partner Gaia Technologies worked together to create a model more suited to the learning aims of younger students. Components of the membrane were researched, and images sent to Gaia to be incorporated in the model. This included the phospholipid bilayer, GLUT1 channels for glucose, oxygen, carbon dioxide, glucose, sodium and potassium molecules, sodium/potassium pumps and carbohydrate chains. Discussions were held by the project group to find a balance between realistic scales and numbers of components. A more realistic representation of the cell structure and scale was used in this model, addressing requests for realism found in Pilot 2. However, some aspects could not be realistically represented in the cell membrane model. For example, to use the correct density of oxygen molecules around the cell membrane would make the model difficult to navigate or see and therefore they were presented as sparser than they would appear in reality. Additionally, standard colours were agreed upon to represent the molecules to avoid the introduction of misconceptions with the use of duller colours as discussed in Section 3.3.3.5.1.7.

Additionally, after the successful trial of the multi-finger haptic device in Pilot 3 (Section 3.3.4.5), two multi-finger devices replaced the single finger device used in previous studies, allowing increased agility in navigating the VR space. The two multi-finger devices used in this study were configured slightly differently (haptic arms either configured horizonal or vertical to each other) by a researcher colleague to compare in their usability and suitability for this activity. Figure 14 shows the vertical configuration, and Figure 15 the horizontal configuration.

Figure 14: Multi-fingered device configured vertically in Pilot 4.

Figure 15: Multi-fingered device configured horizontally in Pilot 4.

As a multi-finger haptic interface was used in this pilot, I decided that the finger section of the Morrisby Fine Dexterity test omitted previously would be relevant to this study. The use of the fingers in a pinching motion in the finger fine dexterity test mimics that of the actions used to manipulate objects with the multi-finger device, and so the skills of the student to manipulate objects using this method were thought to be relevant to the study. Therefore, the complete fine dexterity test (finger and tweezer sections) was used in this study.

The activity was guided with a worksheet (Appendix O), that was developed by the project team and facilitated the user's exploration of the cell membrane and transport molecules by either diffusion or through channels.

A new pre and post-test of cell knowledge was also developed (Appendix P) by the project team. The cell knowledge test for Pilot 2 consisted of one long answer question, however, this method of assessment is limited in its ability to explore learning gains in sufficient detail for the main study. Therefore, the test for Pilot 4 consisted of open, short answer and true/false questions to explore the students' knowledge of the cell membrane and collect more detailed information. These questions included a space to write down statements about the membrane with a confidence indicator (very confident, confident, no idea or guessing), a short answer question about the importance of the cell membrane in the body, and 15 statements with the option of selecting true/false/unsure. Additionally, the post-test in this pilot was administered by researchers during the experiment rather than by teachers after the fact, to avoid the poor return rates seen in Pilot 2 (Section 3.3.3.5.1.6).

A concern that was raised after Pilot 2 was the lack of regulation of the interactions between researcher and student during the task, which has the potential to affect their experience of the system. For Pilot 4, a protocol was developed by a researcher colleague to take a more regulated approach in the instructions and information given to the students by different researchers and avoid variability (Appendix Q).

The results from Pilot 2 showed that there was little range in the scores of the SRT which were approaching ceiling. Although the sample in Pilot 4 was younger than in Pilot 2, the SRT was amended to give a broader measure of spatial relations applicable to this activity. As mentioned in Section 3.3.3.3.3.2, two tests from the Levy and Levy (1999) book of spatial relations tests were identified in the literature as relevant for haptic manipulation in VR: Spatial Views and Solid Figure Turning. It was thought that the Spatial Views test alone would be sufficient for this study's purposes, but with the high scoring, low range scores produced in Pilot 2, the Solid Figure Turning tests were also included in Pilot 4 (Appendix R). Using both Spatial Views and Solid Figure Turning tests increased the number of items from 29 to 51 and so 30 minutes were allotted for the completion of the test.

It was also shown in Pilot 2 that some measures aimed at collecting feedback on the student's perceptions of the system and their learning were not suitable (Sections 3.3.3.5.1.1 and 3.3.3.5.1.5) and did not give the level of detail that was desired.

Therefore, a semi-structured interview was used in this pilot to provide richer data and allow opportunities for the researcher and participant to elaborate on points raised by students, which an online form would not provide.

3.3.5.2.2 Participants

Ethical approval was granted by KCL research ethics office (Appendix S). Thirty-two students were recruited by volunteer sampling from our two partner schools (24 female, 8 male). The students were in year 8 (aged 13-14) and had not yet studied cell biology.

3.3.5.2.3 Procedure

Pilot 4 took place in school laboratories within each of the two schools. Information sheets (Appendix T), consent forms (parental and student, Appendix U) and pre-activity tests (Appendix V) were completed prior to the activity as a group, and post-activity cell knowledge test questions, SRTs, BDT and fine dexterity tests were conducted after the activity. The assessments/activities and their order for Pilot 4 are shown below.

- Pre-activity cell knowledge test
- Haptic familiarisation task
- Haptic cell activity
- Semi-structured interview
- WAIS-III BDT
- Fine dexterity test
- SRT

After reading the information sheet and giving consent, the participants were given the pre cell knowledge test (10 minutes). The pre and post cell knowledge tests were identical to allow a direct comparison of their knowledge before and after the activity. Once complete, students went on to complete the haptic familiarisation task (5 minutes), which was identical to that given in Pilot 2 and gave the students an opportunity familiarise themselves with the haptic device and movement in the VR space. Once familiar with the controls, the participants completed the haptic activity guided by the worksheet whilst being audio and video recorded.

Immediately after using the system, each pair of students participated in a semi-structured interview. The interviews were audio recorded and questions included those about the system and their learning (Appendix W). Following the interview, the psychometric tests were administered including the WAIS-III BDT, SRT and Morrisby Fine Dexterity test.

Finally, a link to a Google feedback form was given to the students to complete in their own time. As the SUS and Learning Loss Scale were found to be unhelpful in Pilot 2, they were not present in the Google feedback form in this study. Although the SUS was not used in its entirety, items from the SUS and NASA-TLX relating to ease of use, physical comfort, and effort required were included.

3.3.5.3 Results and discussion

The results of Pilot 4 came from observation of students, the Google feedback form answers, and the true/false/unsure questions of the pre/post cell knowledge test. This section will discuss the results of this analysis and the implications of these results for the main study.

3.3.5.3.1 Configuration

The vertical and horizonal configurations (Figure 14 and Figure 15) were used in Pilot 4 and bio-engineering researcher colleagues observed differences in students' interactions with the equipment and the suitability of these configurations for the activity. The horizontal configuration allowed the use of a frame that could stand on the laboratory bench and was therefore found to be more appropriate for a laboratory setting. Additionally, the horizontal configuration made the largest range of motion in the forward and backwards directions, allowing users to move deeper within the VR workspace. Consequently, the horizontal configuration was observed to be more suitable for the manipulation of the cell model and therefore was selected for use in further studies.

3.3.5.3.2 Cell knowledge test

3.3.5.3.2.1 Introduction

The aim of piloting the cell knowledge test in Pilot 4 was to trial the suitability of the test structure (a mix of open, short answer and true/false questions) and the language used for the questions on this sample age group. Additionally, answers from the pre and post-tests were compared to examine whether students improved their answers, and if so on which topics. Answer comparisons were also conducted to identify any possible misconceptions stemming from the haptic activity. As Pilot 4 was not aiming to use the cell knowledge scores in detailed quantitative analysis, the whole test was not marked to get an overall score to be compared. Alternatively, a comparison of the true/false/unsure questions between pre and post-tests was examined to gain insight into whether students were learning from the activity and in which topics.

3.3.5.3.2.2 Analysis

The analysis in Pilot 4 was mainly qualitative and used data from the cell knowledge test and the online Google feedback form, which provided feedback on the students' perceptions of the system and their learning.

3.3.5.3.2.2.1 Cell knowledge questions

For the analysis of the cell knowledge test, the true/false/unsure answers for each participant (pre and post-test) were entered into Microsoft Excel 365 to create visual representations of the data. Answer changes were categorised according to how their answers changed from pre-test to post-test. Figure 16 shows a bar graph representing the changes in question answers according to these categories for the entire sample. This graph shows that the most common change is from either an incorrect answer or being unsure at pre-test, to a correct answer post-test (33%). This was followed closely by answering correctly both pre and post-test (29%). These findings were encouraging, as most participants either actively changed their answers from incorrect or unsure to correct, or answered correctly both before and after the activity, suggesting they were not misinformed or confused by the activity. However, there were (albeit fewer) answers changing from correct to unsure or incorrect (12%), or not changing from incorrect (7%) or unsure (8%), suggesting that there was some confusion.

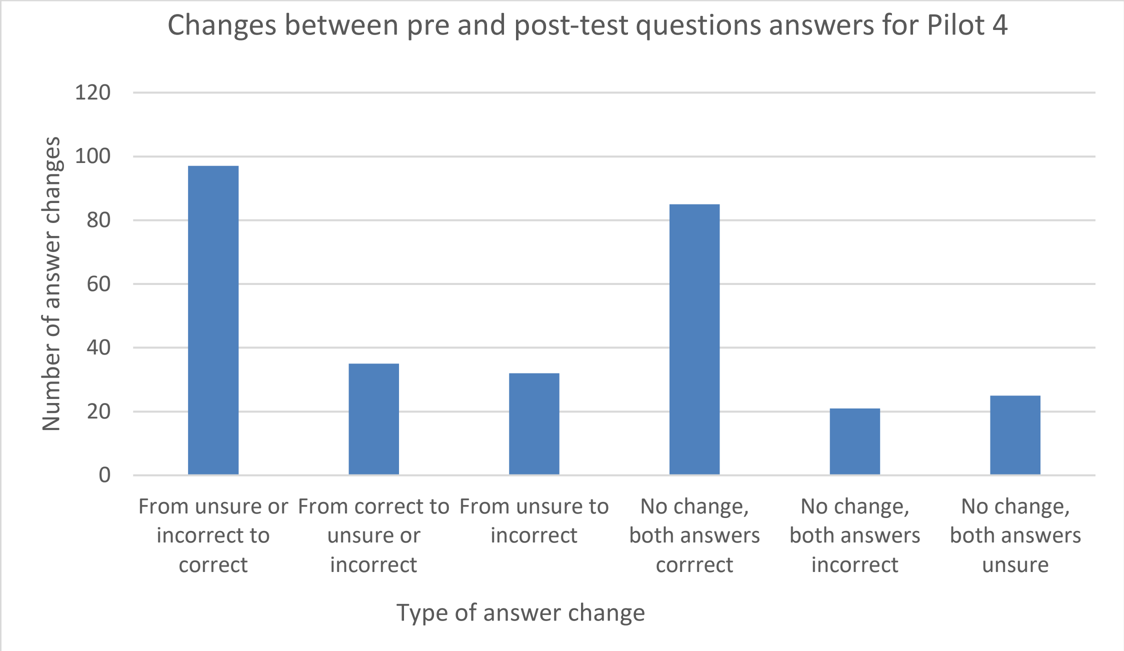


Figure 16: Changes between pre and post-test question answers for Pilot 4

To investigate further, bar graphs were made for each question on the test, showing whether participants changed their answer from pre to post-test and if so, what changes were made (Appendix X).

The graphs in Appendix X suggested that knowledge of certain topics was positively impacted by completing the activity. For example, for statements such as 'the plasma membrane is a barrier that stops everything from entering/exiting the cell' and 'glucose can freely enter and exit a cell (does not need a channel)', most participants answered correctly pre and post-test (9/20 participants; 45%) and most of the remainder showed positive answer changes from incorrect or unsure to correct (7/20 participants; 35%). This suggested that students who knew the answer before the activity were not mislead or misinformed on these topics, and that some students gained knowledge or corrected misconceptions by completing the activity. Answer changes for the statement 'oxygen can freely enter and exit a cell (does not need a channel)' were particularly successful, as all participants either answered correctly pre and post (7/20 participants; 35%) or changed from an incorrect or unsure answer to the correct one (13/20 participants; 65%).

Additionally, Statements 8 (carbon dioxide can freely enter and exit a cell (does not need a channel)) and 10 (glucose is smaller than oxygen) are examples of questions in which most correct post-test answers came from changing from an incorrect or unsure answer pre-test rather than the student already knowing the answer. For example, in Statement 8, 14/20 participants (70%) changed their answer from either incorrect or unsure to correct, with 3 (15%) answering correctly both pre and post-test. In Statement 10, 13/20 students (65%) changed their answer from either incorrect or unsure to correct, with 7 (35%) answering correctly pre and post-test. Findings from these statements suggested that the activity may have been particularly helpful for these topics. On the other hand, statements referring to respiration (Statements 14 and 15) showed that students had a good grasp of the topic, with most answering correctly both pre and post-test (19/20 and 13/20 participants respectively).

However, some questions had mixed results. For example, Statement 9 (sodium can freely enter and exit a cell (does not need a channel)) resulted in 8/20 (40%) participants changing from either a correct or unsure answer to an incorrect one. Statement 11 (the plasma membrane contains about 20 glucose channels) resulted in 11/20 students (55%) changing from an unsure or incorrect answer to the correct one, however, 30% of the participants still answered unsure both pre and post-test (30%) and therefore did not benefit regarding this topic. Additionally, Statement 4 (the plasma membrane contains membrane proteins that sit in a fixed position in the membrane) showed similar numbers of participants in each answer change category (Appendix X), suggesting confusion on the topic.

The results of Statement 3 (the plasma membrane is transparent) identified a potential issue, as most participants changed from either a correct or unsure answer to an incorrect one (15/20; 75%). This suggests that the activity or model may have introduced a misconception to the students. Although the membrane is most likely to be transparent, this is impossible to represent within a functional 3D model, and so a balance between realism and functionality was required for this activity.

On the topic of diffusion gradients, Statement 12 (If there is an equal amount of oxygen inside and outside the cell it will be harder for more oxygen to enter than if there is more oxygen outside) resulted in many students remaining unsure (answering unsure both pre and post-test) (7/20 participants; 35%). However, Statement 12 also showed slightly more participants changing from unsure to an incorrect answer (4/20 participants; 20%) than changing from unsure to a correct answer (2/20 participants; 10%). Moreover, Statement 13 (the amount of glucose inside a cell makes no difference to how easy it is for glucose to enter) had mixed results, with similar numbers of students in several answer change categories. For example, an equal number of participants changed their answers from unsure to correct (3/20 participants; 15%) and from unsure to incorrect (3/20; 15%). There were also similar number of participants answering correctly both pre and post-test test (3/4; 15%) and answering incorrectly both pre and post-test (4/20 participants; 20%). 3/20 (15%) students also changed from correct to incorrect. As diffusion gradients are well known to be difficult topics to grasp (Section 2.1.2.1.2), this topic was expected to be a challenge.

3.3.5.3.2.2.2 t-test

The pre and post-test scores from the true/false/unsure questions were used for quantitative analysis to determine whether the activity had resulted in a significant change in test scores from pre to post-test. The true/false/unsure questions were marked, giving 1 mark for each correct answer and 0 marks for incorrect or unsure answers. This provided raw scores for this section of the test, which were subsequently analysed using IBM SPSS statistics 22.

A paired-samples t-test was conducted to compare the pre-tests and post-test scores. There was a significant difference in the scores for pre-tests ($M=6.10$, $SD=1.80$) and post-tests ($M=9.0$, $SD=1.86$); $t(19)=-6.49$, $p<.001$. These results show that there was a significant gain in cell knowledge after using the system and completing the haptic activity. This was encouraging for the main study, as the activity and haptic system in Pilot 4 was successful in increasing knowledge in cell biology overall.

3.3.5.3.3 Google form questionnaire

Findings from the online Google form provided insight into the students' perceptions of the system and highlighted possible areas for improvement. The questionnaire consisted of Likert scale items and open answer questions to gather data allowing a mixture of quantitative and qualitative data. This section will outline the main findings from the questionnaire and implications for the main study.

Out of 32 participants, 16 responded to the questionnaire. The low return rate of questionnaires was likely due to giving the students the form to fill out in their own time, without supervision.

3.3.5.3.3.1 Multiple choice and Likert scale questions

The questionnaire showed that most participants had never used a 3D computer system before, but all stated they would like to use it for studying, with most agreeing that they would like to use it frequently.

The questionnaire asked several questions about the usability of the system and it was found that participants rated the difficulty of rotating objects as mostly moderate, whereas moving objects was found to be fairly easy. Students also responded that they mostly achieved what they wanted to do with the system, but some also reported that they had to think hard about how to use the interface to achieve their goals. This suggests that the system may have been cognitively demanding for some of the students. Regardless, most students reported that the interface was easy and not frustrating to use. Respondents also stated that coordinating the task with their partner was easy, suggesting that the collaboration aspect of the activity was well integrated.

Overall, the multiple choice and Likert scale questions create a positive picture of the usability of the system from the students' perspective. Responses suggested that most students found the system easy to use, with moderate difficulty in rotating objects, and some feeling like they had to think hard about how to achieve their goals.

3.3.5.3.3.2 Open-ended question responses

The open-ended questions in this questionnaire also focused on the students' perceptions of the system and their learning and allowed for elaboration on some of the previous multiple choice or Likert scale items.

Regarding what the participants liked about the system, recurring points were that students liked using the VR haptic device due its hands-on interactivity (being able to touch and interact with the cell), the collaborative learning style (learning with someone else, or having someone else to work with) and how it was 'fun' to use. Students also reported that the system was useful as it gave them the chance to see things they cannot usually see in practical experiments, which relates to the unobservable nature of the cell membrane and its processes. The hypothesis testing component of the activity was also mentioned, with one student saying that it helps generate more questions when something happens unexpectedly during the activity.

Students commented that it was useful to feel and manipulate the cell membrane virtually as it lowered the need to imagine the whole process and that it was more enjoyable than being told by a teacher. Combined with the collaborative element to the task, one student also mentioned that feeling the membrane facilitated discussion and description in pairs, which may aid memory. Although most commented positively on this aspect, there were some disagreements. For example, one student commented that they thought they would have learned the same from taking notes using a textbook, and another felt they needed more haptic content. Overall, most participants repeatedly mentioned that feeling and seeing the cell membrane and learning in a ‘fun’ way would help their memory.

Participants were also asked what they would change about the system or what they would like to see built into the system. Technical issues were mentioned here, including glitches, and freezing of the program, slipping of fingers from thimbles (contacts for the thumb and forefinger) and restriction of the workspace. A recurring point was also the difficulty in grabbing particles in the model. These points were addressed for the main pilot with the development of the system and its components. Some interesting requests were made which were beyond the scope of this project, but which may be relevant to future research. This included several mentions of having a more immersive world where the whole body could be inside the cell, or that several people could view and manipulate the same cell model at one time. Additionally, some students mentioned the possibility of having small games inside the VR world, which required you to interact with the membrane, allowing them to work on the system by themselves.

3.3.5.4 Conclusion

In conclusion, the cell knowledge questions have shown that for Pilot 4 there was a significant increase in cell knowledge overall (as measured by the true/false/unsure questions from the pre/post-tests), suggesting that the activity was successful in facilitating learning. As seen in 3.3.5.3.2, most changes in answers overall were from incorrect or unsure to correct, further supporting the evidence for positive learning gains during the pilot. Additionally, the changes in the answers of these questions suggest that certain topics were addressed successfully including the function of the plasma membrane, how glucose, oxygen and carbon dioxide pass through the membrane, respiration, and the size of oxygen relative to glucose. The activity involved moving the molecules through the membrane, the differences between oxygen and glucose in their movement and presented the relative sizes of the molecules visually throughout the activity, so these topics were expected to show successful learning outcomes.

However, the answers for some of the statements suggested that certain topics were not well understood, and the activity may need to be amended to address this. Topics that seemed to need further work included the diffusion gradient between the cell membrane and its effects on molecules, membrane proteins and the transparency of the membrane. These topics are more difficult to understand and were identified in this pilot as possible areas to focus on in further development.

The feedback form showed that although generally the students enjoyed using the system and thought that feeling and seeing the cell membrane would help their learning in some ways, there were also technical faults interrupting their activities and distracting them from their learning objectives. It was also noted that some students felt that they had to think hard about how to achieve their goals with the system, which may mean that the student was distracted from the biological content by the technical aspects of the system. Additionally, observational data helped inform the decision that a horizontal configuration for the haptic system was most appropriate for this project.

The results of Pilot 4 were used to guide the improvement of the system and activity by addressing the technical issues and revisiting the model to reflect which topics students found particularly difficult. The next section will discuss the final pilot test before the main study, which considers the issues identified in Pilot 4.

3.3.6 Pilot 5: PGCE focus group

In the continuing development of the system and activity, it was thought that getting more detailed feedback from biology educators unattached to the project would be helpful in identifying areas of improvement or possible issues before further testing on school students. Therefore, a sample of PGCE biology students (trainee biology teachers) at KCL were recruited by volunteer sampling to participate in Pilot 5. Pilot 5 involved trainee biology teachers using the haptic VR environment and completing an activity expected to be used for the main data collection. This was followed by a focus group to explore their opinions on the difficulties in teaching cell biology, their thoughts on the potential for haptics to benefit biology learning and any concerns or perceived barriers to integrating haptics into regular classroom teaching.

Focus groups are group interviews where small numbers of people discuss a topic that the interviewer raises. Focus groups work best when what interests the research team is equally interesting to the participants in the groups (Morgan, 1997). As the participants were trainee biology teachers, the topic of using new technology in classrooms to benefit learning in their subject was of interest to them. Focus groups can help generate topics, constructs and issues to be addressed and meet the objectives of research (Cohen et al., 2017), and can be used in implementation stages of projects to fine tune plans and offer insights into the implementation so far (Morgan, 1997). For these reasons, a focus group was identified as a useful research method at this stage of development.

This section will outline the developments made since Pilot 4, methods used in Pilot 5, procedure, and results (including implications for the main study).

3.3.6.1 Design and methods

3.3.6.1.1 Development since Pilot 4

As mentioned in Section 3.3.5.3.2.2, Pilot 4 identified issues involving the technology (including glitches, freezing and thimbles slipping) and the educational content (including confusion over topics involving diffusion and membrane transparency). Between Pilots 4 and 5, development of the system took place, including improvements to the model, the equipment, and the activity. Table 4 summarises the challenges from Pilot 4 and how they were addressed in Pilot 5.

Table 4: Challenges from Pilot 4 and how they were addressed in Pilot 5

Challenges	How they were addressed in Pilot 5
Confusion over diffusion topic	New activity exploring the diffusion gradient for oxygen, carbon dioxide and glucose. The ability to add and take away molecules from the model Diffusion gradient across the membrane in development
Bug: instability in glucose molecules	Bug fixed
Confusion on what the membrane proteins were	Added a label
Slipping thimbles	New thimbles trialled with Velcro
Transparency of the membrane	Not addressed
Navigating the 3D space	Multiple speeds added to aid manipulation of molecules. 'Flat' cursor design to aid in grabbing objects.
Limited workspace	Vertical membrane design.

Using the findings from Pilot 4, a new activity was designed by the project team and a suitable model created by bio-engineering researcher colleagues. The new model was part of a cell membrane, which could be used to explore the topic of diffusion gradients (which was identified as a difficult topic in Pilot 4). The worksheet for Pilot 5 (Appendix Y) was amended to focus on the diffusion gradient and how it affects diffusion across the membrane. Although a preliminary haptic force was implemented for glucose passing through the glucose channel, unfortunately, the diffusion gradient force across the membrane was still in development. Therefore, the diffusion gradient was not fully implemented for this pilot. Additionally, the ability to add and remove molecules from the model was added.

Some technological issues were also addressed by stabilising molecules and amending the thimbles to adjust with Velcro to avoid slippage. There was some confusion observed in Pilot 4 as to what the membrane proteins were, which prompted the inclusion of a label in the model. Some improvements were also made for navigation in the 3D space. A flat cursor design was implemented to make grasping easier, as well as a multi-speed setting that allowed the user to slow down or freeze the model. This feature had the bonus of having a default high speed of movement for the model, showing a more realistic idea of how fast and dynamic the membrane is.

Feedback from Pilot 4 showed that students had commented on the restricted workspace and requested more space to manoeuvre. A solution to increase the workspace was to move the membrane from a horizonal to a vertical position in the VR space, as the haptic interface allowed for more movement forward and backwards in the VR space using this orientation to grab and manipulate molecules. It was discussed by the project group that there were no educational reasons to keep the membrane horizontal, and it was commented by biologists in the project group that having the membrane vertical may discourage the misconception that the force of gravity works on the molecules at this micro-level. However, as a horizonal model is typical in textbooks, the change in orientation was to be addressed in the focus group to gather further opinions from educators on the matter.

Although some confusion was found in Pilot 4 regarding the transparency of the membrane, it was not possible to demonstrate transparency in the model for this activity and so this was not addressed, in favour of attempting to address the difficult subject of diffusion, which requires a clear and visible membrane.

3.3.6.1.2 Participants

Ethical approval was granted by KCL Research Ethics Office (Appendix Z). Participants were part of a cohort of trainee biology teachers on the PGCE biology course at KCL. After being presented information on the study, 13 participants were recruited via volunteer sampling.

3.3.6.1.3 Procedure

The activity took place in a teaching laboratory in KCL during a practical session. After being given information (Appendix AA) and signing consent (Appendix BB), participants used the haptic system in pairs (and one group of 3). A haptic familiarisation task (as used in previous pilot tests) was not used in Pilot 5, as findings from Pilot 3 suggested that the multi-fingered system was more intuitive and time constraints made implementing familiarisation difficult. Guided by a worksheet, the pairs completed an activity, describing how the membrane felt, moving oxygen, carbon dioxide and glucose through the membrane, using glucose channels, ordering molecules by size, and hypothesising what would happen when adding and removing molecules.

Once all pairs were finished, participants moved to a room for the focus group, where a researcher colleague and I lead the discussion which was audio recorded on a Dictaphone. A sheet of questions was used to guide the discussions (Appendix CC) with questions pertaining to the system (how they found using it, what they would change and collaboration), their learning (problems with learning cell biology, benefits of the system, usefulness of the haptic sense and collaboration) and any other comments.

At the end of the focus group, the participants were thanked for their time and the pilot was ended.

3.3.6.1.4 Results and discussion

Results from this pilot came from observations of participants during the activity, the audio recording of the focus group and my hand-written notes during the focus group discussions.

Observationally, the flat cursors seemed to work well and were distinct from other bodies in the VR world. However, the Velcro thimbles were found to be difficult to use and so it was noted that further solutions should be developed. During the activity, it was observed that certain sections would have benefited from additional instructions, such as using different speeds to suit the goal. Additionally, a few software bugs in the system were identified to be fixed before the main study, such as instability in some molecules. The size of the molecules seemed to cause some issues in grabbing them successfully. As a result, many participants would only move the molecules by pushing them, which would be an issue for the main study as students would need to grasp and move molecules to feel the diffusion gradient force. Subsequently, it was suggested that the molecules be scaled up to allow easier grasping in the model. The activity was also shown to take longer than expected and so the worksheet was examined for questions that could be omitted or shortened.

During the focus group, there were several points discussed regarding the system and its usefulness in cell biology and the classroom. Feedback on the system supported that grasping the molecules was an issue and that certain bugs in the system affected its intuitiveness. These bugs and design issues were to be addressed as the haptic system was developed further for the main study. Difficulty keeping fingers in the Velcro thimbles was also discussed, suggesting that a different solution was required.

Praise for the system included the usefulness of the labels, seeing more advanced material (such as membrane proteins), seeing diffusion in 3D and having a more realistic representation of the speed of the processes in a cell. Collaboration was found to be easy in the task and the value of collaboration on the task was discussed including joint problem solving, communication and division of labour. It was also noted that with a co-pilot, the pilot did not have to take the Oculus Rift off to answer question and thus remained immersed in the cellular world. In terms of learning, participants expressed that the system may help students link processes in the cell together at an earlier stage and allow children to be exposed to the cell unit before looking further into individual processes.

However, the lack of haptic feedback in this partly developed system was noted by the participants. Although some noticed the haptic force bringing glucose through the glucose channel, participants largely did not notice the haptic force. The activity did ask participants what certain actions ‘felt like’ and with the lack of diffusion gradient force for this pilot, this was understandably confusing. As the additional haptic forces were being developed this was not much of a concern at this stage, and some expressed that with the haptic force, the activity would be a good experience for biology students.

Potential issues identified in the focus group included the rigidity of the cell membrane. The cell membrane in the model was inflexible and some participants expressed concern that, as the membrane is more flexible, a misconception may occur. This was something to consider in the next stage of development of the model. Regarding the worksheet, it was suggested that the use of the word ‘feel’ in the worksheet may have been misleading as it was an emotional word. This may have been a result of the lack of ‘feeling’ in this system, but it was noted that this instruction may change for the main study to avoid confusion. Additionally, it was mentioned that the worksheet may have been too ‘wordy’, involve too many instructions or have questions that were too long. It was noted therefore for the next study that the worksheet be restructured to be as concise as possible.

3.3.6.1.5 Conclusion

In summary, the results of Pilot 5 identified some issues to be addressed for the main study. These included technical faults including bugs in the software, undeveloped haptic sense, and difficulty with the finger thimbles. There were also issues identified with the worksheet and activity itself, where it was suggested that the wording and structure of the worksheet could be streamlined to avoid confusion. These were issues that were able to be addressed in further development of the system and were useful insights into the user experience. From an educational perspective, the participants suggested that with the haptic sense fully enabled, this system would be useful in representing the cell and its processes to students beginning to learn cell biology. Participants mostly commented on the visual aspects of the system, as the haptics had not been fully developed, but the ability to see diffusion in 3D, to see the processes as part of a whole and to view the dynamic, fast nature of the movement of molecules were mentioned as positive aspects in this pilot. Using these results, the system was developed further for its use in the main study, removing bugs and technical faults so as to limit their distractions in the future. Additionally, the feedback guided the revision of the worksheet to become more concise, better utilise the time available and better match the ability of the students expected to be involved in the main study.

This was the last of the pilot studies before main data collection at our partner schools. The next section (3.4) will discuss the method of the main study including how the issues and challenges from this pilot were addressed, the design of the main study, participants, procedure, and planned analysis.

3.4 Main Study

3.4.1 Introduction

So far, this chapter has documented the development of a 3D, VR learning environment capable of providing haptic feedback and supporting collaborative learning for difficult subjects in cell biology. The rapid prototyping method utilised several pilot tests to guide development (Section 3.3), which involved the identification of topics suitable for the use of the haptic sense, building of the haptic interface, researching and developing the cell model, identification and trialling of relevant psychometric measures, the development of worksheets and assessments of cell knowledge and the identification and correction of unexpected issues. The pilot tests refined and guided development and led to a well-designed, functional system suitable for use for the main study, as well as the identification of suitable measures of spatial ability, fine dexterity, and cell knowledge.

The pilot tests were focused on development; however, the main study was focused on answering the research questions outlined in Section 3.2. To answer RQ1 (will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?), the main study compared two conditions: a haptic condition and a non-haptic condition. The haptic condition allowed users to feel all touch feedback from the model including drag force and concentration gradients across the membrane. The non-haptic condition was identical to the haptic condition, but with all haptic force feedback from the model removed. In the non-haptic condition, students could manipulate virtual objects, allowing them to navigate the virtual space, but all haptic feedback (including diffusion gradients across the membrane and forces acting on the glucose channels) was removed from the system. Comparing these two conditions isolated the educational effect of haptic feedback in this study.

To answer RQ2 and RQ3 (d*oes existing spatial ability/fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?*), spatial ability and fine dexterity scores were used as covariates to control for these factors.

RQ4 (*what design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?*) was answered using qualitative data from semi-structured interviews investigating student's perceptions of their learning, the system, and its use for learning cell biology.

This section will describe the methodology for the main study, including the improvements made after Pilot 5, the design of the main study, participants, procedure, and planned analysis.

3.4.2 Development and changes since Pilot 5

The system continued to be developed until its use the main study, and the results of Pilot 5 helped to identify possible issues to be addressed. Table 5 summarises the challenges identified in Pilot 5 and how they were addressed in the main study.

Table 5: Challenges from Pilot 5 and how they were addressed in the main study

Challenges from Pilot 5	**How they were addressed in the main study**
Slipping thimbles	Use of rubber finger inserts and tape to secure fingers in thimbles.
Technical faults and bugs	Coding fixed.
Undeveloped haptics	Haptic diffusion gradient and drag force added to the model.

‘Wordy’ worksheet and running over time	Worksheet revised to become more concise.
Possible misconceptions of the rigidity of the membrane	Not addressed.
Using the phrase ‘how does it feel’ in the worksheet	Using ‘what you think you feel and observe’.

As the system’s new activity was still being developed during Pilot 5, the technical faults and bugs (including unstable components and freezing) were addressed for the main study by the developers of the haptic environment at the University of Reading. Additionally, a solution for the detachment of fingers from the thimbles was addressed by using rubber finger inserts and tape to secure fingers better to the haptic device.

Haptic feedback was implemented in the model, including the concentration gradients and drag forces used to demonstrate the processes across the cell membrane. Unfortunately, the rigidity of the membrane was not able to be addressed in time for this study. To implement fluidity into the membrane was a complex design issue, as it was complex to program the membrane to react to objects going through it in a fluid way. The membrane was programmed for objects to either pass through or not pass through, with the glucose transporters implemented as simulations which gave the impression of a semi-permeable barrier. It was discussed with the project team that it was possible to superimpose a simulation onto the membrane, but this would have required extensive additional programming and may have been confusing for students. Therefore, it was decided by the design team that compromises were essential on the modelling of the cell membrane, which included a rigid appearance.

Although the trainee biology teachers identified this possible misconception in Pilot 5, the results of Pilot 4 (Section 3.3.5.3.2.2.1) suggested that most students on the question regarding the solidity of the membrane changed their answers from either incorrect or unsure to correct. This suggested that the possible misconceptions from the rigidity of the cell membrane model was not of critical concern but is something that could be addressed in further research.

As discussed in Section 2.1.3, the literature concerning misconceptions and misunderstandings in cell biology presented some recommendations for the use of 3D VR, including using less stylized and more realistic images (Meir et al., 2005; Tibell & Rundgren, 2010). A balance was struck in development of the model in this study between realism and the capabilities of the technology and features necessary for the usability of the system (discussed in Section 3.3.5.2.1). Molecules and cell components were sized as realistically as possible without compromising students' ability to interact with them. Compromises included presenting molecules as sparser than reality to allow students to view and interact with molecules effectively and using standard colours common to traditional learning materials to represent molecules so as to avoid introducing additional misconceptions with the use of duller colours (as discussed in Section 3.3.3.5.1.7).

With feedback from Pilot 5, the worksheet was revised to be clearer and more concise, adding simpler instructions and, after discussions with biologists and teachers from the project group, removing superfluous questions. Additionally, due to feedback from Pilot 5, wording referring to what the membrane 'feels like' was clarified by a researcher colleague and changed to what they 'feel and observe' to avoid emotional connotations. The final worksheet used in the main study can be seen in Appendix DD.

Additionally, for the main study, the WAIS-III BDT subset was replaced by the WISC-IV (Wechsler, 2003). As discussed in 3.3.3.5.1.3, the WISC test was more appropriate for the age of participants in this sample and with consultation with a psychologist it was decided that the WISC-IV would be used for the main study.

The result of these revisions was a functional system and activity for use in the main study. The activity and worksheet were designed to allow interaction with a cell membrane and diffusion, and to allow peer discussion and opportunities to hypothesise (by asking students what they expect to happen), which has been suggested to improve engagement and motivation in biology (Odom, 1995).

3.4.3 Design

The main study was a 2x3 repeated measures design. There were two independent variables (IVs). The first IV was the time at which students took the cell knowledge test, which had 3 levels: pre-intervention, post-intervention, and retention (8 months after the intervention). The second IV was the ‘condition’ with two levels: haptic (touch feedback enabled) and non-haptic (touch feedback disabled). Dependent variables included the cell knowledge test scores, spatial ability scores (BDT and SRT) and fine dexterity scores.

The study was repeated measures, as all participants completed the pre-test, post-test, and retention-tests. There was also a between subjects measure, as the participants were also separated into two conditions: haptic and non-haptic. Spatial ability and fine dexterity were also recorded for all participants to be used as covariates in planned analysis.

3.4.4 Test of Cell Knowledge

The aim of the assessment was to measure general knowledge of cell biology and to measure any learning gains after taking part in the intervention. The development of the assessment took into consideration concepts identified in the literature review as being difficult for students to understand, often due to their abstract nature and prevalence of misunderstandings and misconceptions. A table presenting each assessment item, their associated concepts/misconceptions, whether they are addressed in each condition, and how they relate to theory can be seen in Appendix EE.

The test of cell knowledge for the main study (Appendix HH) consisted of three questions in the same format used in Pilot 4. Question 1 allowed space for five statements about the membrane with a confidence indicator (very confident, confident, no idea or guessing). Question 2 was a short answer question about the importance of the cell membrane in the body. Question 3 contained 14 statements about the cell with the option of selecting true, false, or unsure.

Question 1 and 2 were scored using a rubric developed and agreed upon by the project group, which included Biologists and Biology educators. The rubric scored answers on a scale of 0-7 depending on whether answers were correct, incorrect, simple, or complex. Table 6 shows the categories and associated scores for this rubric. The maximum score for Question 1 was 35 (5 statements with a maximum score of 7 each), and the maximum score for Question 2 was 7. Questions 1 and 2 were marked by an independent biology expert from the project group, who had not interacted with the students and could therefore provide an objective assessment of their answers. The aim of the assessment was to compare between students, and as the mark scheme was agreed upon by the project group and employed by an independent expert assessor, IRR (inter-rater reliability) tests were not deemed necessary.

Table 6: Rubric scores and categories used to score Questions 1 and 2 of the main study cell knowledge test

Rubric category	**Rubric Score**
7	Correct complex
6	Correct less complex or complex but partially wrong
5	Correct simple
4	Correct very simple or partially wrong
3	Partially correct mostly wrong

2	Wrong
1	Unclear/irrelevant
0	Misunderstanding

Question 3 was scored by allocating 1 mark for correct answers, and 0 marks for incorrect or unsure answers. The maximum score for Question 3 was 14. Therefore, the maximum score for the cell knowledge test was 56.

3.4.5 Participants

In total, 74 participants were recruited via opportunity/volunteer sampling (m=34, f=40). All participants attended two partner schools (one girls', and one boys' school) involved with the project. All participants were in their first term of year 8, aged 12-13 years. Both schools were independent, selective secondary schools in the South of England. All participants had yet to study the cell in their biology lessons, making the activity used in this study a learning exercise. Thirty-eight students were allocated to the haptic condition and 36 to the non-haptic condition.

3.4.6 Procedure

To efficiently utilise the time available in schools for the main data collection, the main study was separated into two phases. Phase 1 involved me attending the partner schools over several days to provide information sheets, collect consent and administer the pre-test, spatial ability tests, and fine dexterity test. Phase 2 was the main data collection involving myself and several project team members, which included the haptic activity, the post-test, and the interview. This section will describe the procedure of each phase.

3.4.6.1 Phase 1

After obtaining parental consent (Appendix FF), Phase 1 began by explaining the purpose of the experiment to the participants and providing them with an information sheet and student consent form (Appendix GG). The participants were not aware of the two conditions in the experiment, only that there were two different systems.

After giving consent, participants were given the pre-cell knowledge test (Appendix HH) and the SRT on paper (used in Pilot 4, see Section 3.3.5.2.1).

The WISC-IV BDT subtest was administered to each participant individually (Appendix II). The procedure was identical to that described in Section 3.3.3.3.3.1, as the only differences between the WAIS-III and WISC-IV BDT subsets were the designs presented to the participants to replicate.

The Morrisby Fine Dexterity test was also administered individually as described in Section 3.4.4, and included both finger and tweezer sections (as discussed in Sections 3.4.4 and 3.3.5.2.1).

Overall, Phase 1 included the administration of the following tests:

- Information and consent (10 minutes)
- Pre cell knowledge test (12 minutes)
- SRT (30 minutes)
- WISC-IV BDT subset (15 minutes)
- Morrisby Fine Dexterity test (8 minutes)

3.4.6.2 Phase 2

Phase 2 involved the main data collection, which took place on 2 consecutive days at each partner school. This data was collected by several members of the project team, including myself.

To begin Phase 2, participants were paired together by convenience/chance (when students could be excused from their lessons and in what order they arrived) and were allocated to a haptic device. Each pair began with one participant as the pilot and the other as the co-pilot. The basic instructions were given to the students according to the researcher protocol (discussed in Section 3.3.5.2.1). The participants were given the worksheet and began the activity whilst being audio and video recorded.

The activity involved the students interacting with a cell membrane in the virtual world (Figure 17). Students were able to explore the membrane and move oxygen, carbon dioxide and glucose molecules within the cell and through the membrane. The worksheet guided the participants to explore and describe what they felt and observed whilst completing the activity, including bringing attention to the differences in concentration gradient with more or fewer molecules on either side of the membrane.

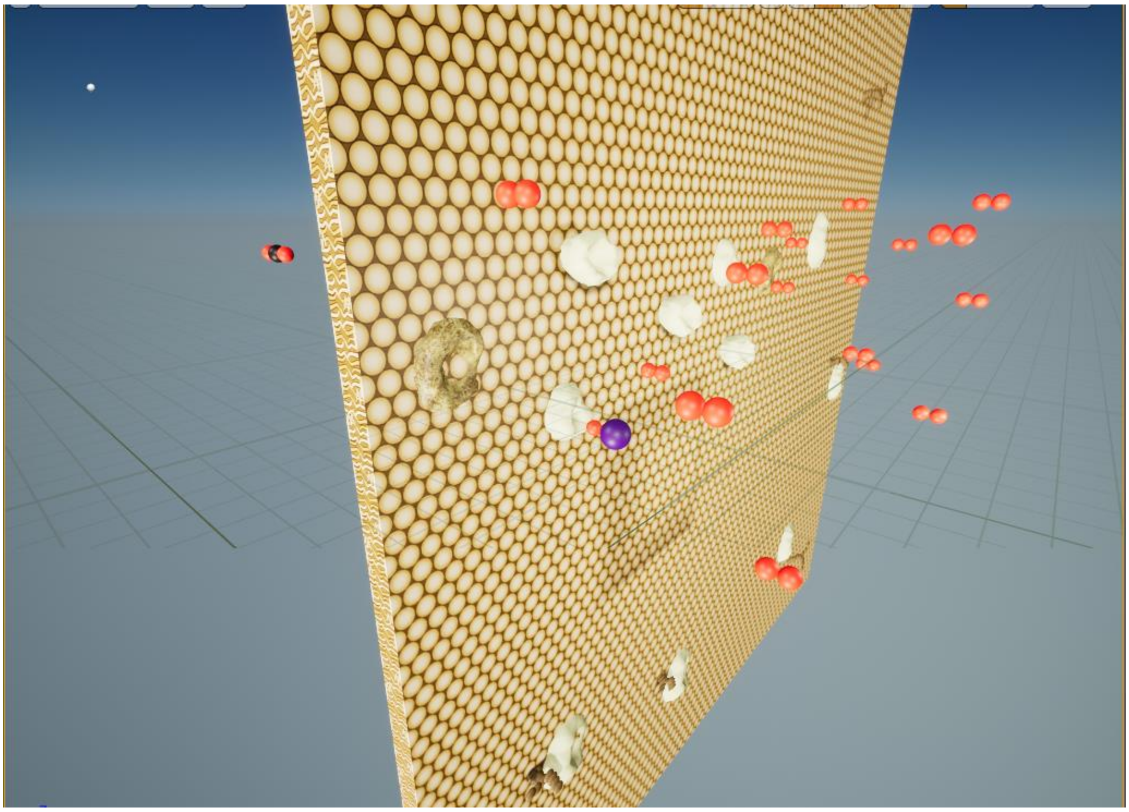


Figure 17: Screen-capture of the membrane model used for the main study.

Once the participants had completed the activity, they were asked to complete cell knowledge test again, which acted as the post-test.

Following the post-test, participants were taken in their pairs to another area (often a study area, or faculty office) to conduct the semi-structured interview to gather their perceptions of the system and their learning. Each interview involved one interviewer (one of three different researchers, including myself) with one pair of students, and was audio recorded with a Dictaphone. The interview was guided by a list of interview questions, but as this was a semi-structured interview there was flexibility for the interviewer or interviewee to elaborate and deviate from the script should it be deemed relevant. The methodology of the interviews is discussed in more detail in Section 3.4.8.

After the interview was completed, this was the end of Phase 2 and the experiment. The participants were thanked for their time and returned to their lessons.

3.4.7 Planned analysis

For this study, both quantitative and qualitative data was planned to be analysed to complement each other and gather a more complete picture of results of the study (Section 3.2). This section will outline the data collected and how it was planned to be analysed.

3.4.7.1 Quantitative data

Quantitative data gathered in the main study consisted of the following:

- Pre, post, and retention cell knowledge test scores
- BDT scores
- SRT scores

- Fine dexterity scores (including both finger dexterity and tweezer dexterity sections)

To determine any significant difference between pre and post cell knowledge test scores, a paired sample t-test was planned to be conducted using IBM SPSS statistics 22 (used for all inferential statistics in this study). This would determine whether the haptic activity resulted in any gain in knowledge for the sample overall.

For comparing the change in cell knowledge test scores from pre to post-test between the haptic and non-haptic conditions, a 2x3 mixed ANOVA was planned to be conducted. This test uses the within subjects data (pre, post and retention-test score) and the between subjects data (haptic or non-haptic condition) to determine significant differences.

The BDT, SRT and fine dexterity scores were planned to be included as covariates in a 2x3 mixed ANCOVA (for pre, post and retention-test analysis). This test controls for BDT, SRT and fine dexterity variables by entering them as covariates and identifying significant differences between the conditions according to their pre, post and retention-test scores.

Additionally, an analysis of the true/false/unsure section of the cell knowledge test was planned, whereby the answer changes from pre to post-test were quantified for the overall sample and compared by condition. Analysis of the true/false/unsure section was planned to provide more detail on which concepts may have been affected by the intervention and to what extent, allowing a more detailed discussion of how student's knowledge may have changed from pre to post-test.

3.4.7.2 Qualitative data

Qualitative data in this study refers to that of the semi-structured interview. The audio recordings of the interviews were transcribed using a transcription service (waywithwords.net) which I subsequently checked for errors. The planned analysis for this data was a thematic analysis of all transcripts using NVivo 11 to identify recurrent and salient themes. The interviews are discussed in more detail in Section 3.4.8.

The following Results chapter will describe the analysis of both the quantitative (Section 4.2) and qualitative (Section 4.3) data mentioned here in detail and report the findings.

3.4.8 Interviews

3.4.8.1 Introduction

As explained in Section 3.2, MMR is used for a more comprehensive understanding of the research problem than any method in isolation can provide. Although quantitative measures are used to address RQ1, RQ2 and RQ3 (Section 4.2), RQ4 (*what design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?*) required qualitative methods for more in-depth data.

As discussed in Chapter 2, this question is exploratory in the research area, as reviews have stated that although there is potential for haptics to be used for science education, studies are often contradictory and further research is needed to fully understand the role haptics may play in learning science (Section 2.4.3). Therefore, utilising students' perspectives on their learning in relation to the haptic activity may gain insight into how they feel they did or did not benefit and might or might not benefit further from this kind of technology.

In this research, semi-structured, audio recorded interviews were used, which were then open coded and analysed thematically. In this section, the rationale for using these methods will be explored and the procedure of the interviewing and analysis will be explained in detail.

3.4.8.2 Choosing the interview method

As described Section 3.3, surveys and questionnaires were used in pilot testing to gather information on the students' perspectives of the system for the development of the system, and the activity. A disadvantage with using surveys and questionnaires, however, is that it is an impersonal medium and ideas and concepts cannot be followed up with ad-hoc questions, restricting the amount of information gathered. There is also a risk of data loss via non-respondents and misunderstanding or confusion over questions which may result in unreliable or irrelevant data (Cohen et al., 2017). Interviews however, allow participants to discuss their perspectives and express how they regard situations from their own point of view in conversation. Interviews allow a degree of flexibility, allows the participants to speak according to their own wishes and allows the interviewer to rework questions, point out contradictions and make connections (Denzin & Lincoln, 2011).

As interviews are a conversation between two people, it is possible that as a result of taking part in the interview, the interviewee may think about their perspectives and experiences in a different way as the conversation progresses, therefore potentially altering the data from what they would otherwise report with no additional input from others (Curtis & Curtis, 2011). Potential disadvantages in adding the interviewer into the data collection can be countered with careful preparation and planning to design questions to accurately reflect the students' perceptions and attempting to understand what the interviewee meant by what they said instead of relying solely on how it is expressed (Willig, 2013). Additionally, building rapport with the students can help them feel able to communicate honestly and openly (Gill, Stewart, Treasure, & Chadwick, 2008).

Flexibility, the exploratory nature, and potential for a broad range of analysis make interviewing a useful method for this study as it allows the flexibility to explore students' perceptions of their learning. Interview data can be rich and detailed, and in-depth analysis can be conducted to explore concepts and themes that emerge from it. Therefore, interviews were a suitable method for exploring how haptics could enhance or inhibit students' learning.

3.4.8.3 Sampling

In this study, after completing the haptic activity, pairs were interviewed on their experiences. Thirty-one interviews were conducted: 15 from the haptic condition and 16 from the non-haptic condition. Concerning sample size in qualitative research, Patton (1990) has stated there is no ‘hard and fast rule’ for sample size, and that in depth information from a smaller sample can be valuable and has the potential to provide rich data. In addition, Holloway and Fulbrook (2001) has posited that, as the goal of qualitative research is not to generalise amongst a population, sample size has less importance as long as enough data can be gathered to fully explore the research question.

Lincoln and Guba (1985) suggest four categories to inform researchers when to stop collecting and processing qualitative data. These included one or more of the following: exhaustion of sources, saturation of categories (the gain in information is small compared to the effort in continuing sampling), emergence of regularities (a feeling of integration) and overextension (new information emerged is far away from existing data). A pragmatist approach (Patton, 1990) was most appropriate for determining sample size in this research, as the sample depended on the resources available and what was credible within the timeframe in these locations. For this research, the sample size was constrained by the number of pairs that were available, and as additional data collection was not practical, this would fit in the ‘exhaustion of resources’ category.

Additionally, it was found that by the end of coding, little new information was being revealed with each subsequent interview. The small amount of new information emerging by the end of the thematic analysis corresponded to the saturation category from Lincoln and Guba (1985), and also suggested that the goal of exploring the data fully by Holloway and Fulbrook (2001) was satisfied. Therefore, although sample size was restricted in this study, it seemed, according to the work of Lincoln and Guba (1985), Holloway and Fulbrook (2001), and Patton (1990), the sample size for this analysis was satisfactory.

3.4.8.4 Development of interviews

The aim of these interviews was to gather information on the students' experiences of the haptic activity. More specifically, the interviews were used to help answer the following research question: *What design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?*

Firstly, the interviews were used to gather the students' perceptions of whether the system had enhanced their learning or supported their understanding of difficult concepts in cell biology, as well as how the system compared to regular teaching. The interview also aimed to illicit information to be used to further develop the system, such as the students' opinions of the technology, its ease of use and possible improvements for the future.

The interview was developed collaboratively by the project team involving biologists, bioengineers and education researchers. A semi-structured interview was chosen for these interviews by the project team, which started with predetermined questions but allowed room for expansion on relevant responses by the interviewer and also for the expansion of the material according to what the interviewee saw as relevant (Freebody, 2012). For a semi-structured interview, the schedule was prepared but allowances were made for the re-ordering and expansion of topics. As the aim of these interviews included gathering perceptions, opinions and explanations, a semi-structured approach was useful as it was focused enough that there was not too much information extraneous to the study (Lofland & Lofland, 1995), but allowed the flexibility for participants to raise issues that might have been missed in a completely fixed schedule (Cohen, Manion, & Morrison, 2007).

For the pilot tests, an interview schedule was created containing questions based on two categories: the system and the students' learning (Section 3.3.5.3.3). These questions were created collaboratively by the project group to gather information pertaining to the research questions and to the wider development of the system. The questions were also designed to reflect concepts from other assessments of usability such as the NASA Task Load Index but were adapted for younger participants. After reviewing the pilot interview content, the project team reviewed the questions and refined them to reflect their ability to gain the information required, as well as using emerging topics to add specific questions and clarifying terminology to reflect the students' age and level of understanding. The revised interview schedule for the main study (Appendix JJ) contained questions based on 3 categories: the system, the students' learning, and comparison with regular teaching.

3.4.8.5 Conducting interviews

Interviews took place directly after completion of the activity and post-test, and students were interviewed in the same pairs they were in for the activity. The interviews took place in dedicated science laboratories or small offices within the host schools.

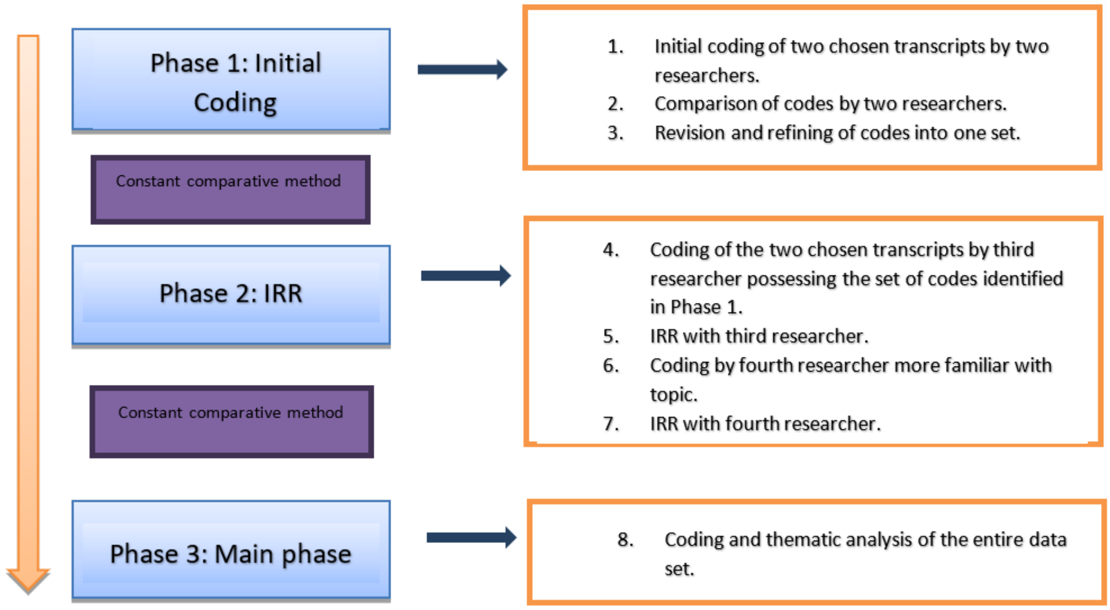
The interview schedule was used to guide the interview, but topics were open to follow what the interviewees found relevant. As I (and the other researchers involved) had met and interacted with the participants prior to the main data collection, the style of interview adopted was that of a conversation, with an aim to utilise rapport and encourage honest information sharing (Gill et al., 2008). We also made sure to reiterate to students before the interview that there were 'no right or wrong answers' and we were interested in their opinions and perspectives.

Each interview was recorded on a Dictaphone and hand-written notes were made discreetly (to not pull attention away from the conversation) (Willig, 2013) during particularly salient or surprising points (Appendix KK). A transcription service was used to transcribe the interviews (www.waywithwords.com). I checked each transcript whilst listening to the audio tapes to correct errors or previously inaudible content and anonymised the content with pseudonyms. Whilst listening to the interviews at this stage, notes were also taken on initial impressions of the content (Appendix LL).

3.4.8.6 Interview analysis

To meet the aims of the interview analysis, a method of analysis was needed which could identify important information and patterns to help derive meaning from the dataset. It was decided that thematic analysis was the most suited to this project as it allows searching across a data set to find repeated patterns of meaning. Additionally, consistent with the pragmatic approach of 'what works', thematic analysis has been described as a method of analysis that can be applied across a range of theoretical and epistemological approaches and has the ability to yield rich and varied data (Braun & Clarke, 2006). Thematic analysis allows exploration of the students' perceptions whilst allowing unexpected themes to emerge without determining their importance beforehand or restricting to prearranged concepts (Marks & Yardley, 2003). For these reasons, thematic analysis was chosen as the most appropriate for this research and its aims. This section will describe the steps from raw data to thematic analysis, including open-coding in NVivo, code comparison with other researchers, refining methods, inter-rater reliability, and identification of themes. Figure 18 shows a visual representation of the stages in coding and thematic analysis, which will be explored further in Section 3.4.8.6.1.

Figure 18: Flow diagram of the phases involved in the qualitative interview analysis



3.4.8.6.1 Coding

Coding of the data was structured according to Braun and Clarke (2006), who provide a well-cited step-by-step method for thematic analysis with six phases: familiarising with the data, generalising initial codes, searching for themes, reviewing themes, defining and narrowing themes and producing a report. In this section, the process of thematic analysis for the interview data will be described, referring to the steps outlined in Figure 18.

3.4.8.6.1.1 Phase 1: Initial coding

To begin the coding process, I familiarised myself with the data by checking each transcript against the audio recording, followed by repeated reading of the transcripts. Notes were made of salient or recurring points and potential items of interest.

After familiarising with the data, two transcripts were initially chosen to be coded and used to assess the reliability of the coding method. Only two transcripts were chosen as this was thought to be an acceptable amount of information with which to check reliability of coding between researchers (Miles & Huberman, 1994). The initial two transcripts were chosen for their good amount of dialogue and potential for rich content. These two transcripts were coded by two researchers (my supervisor and I) openly, with no predetermined codes or explicit expectations for which codes should emerge. The method of coding and analysis outlined by Braun and Clarke (2006) was used for the initial two transcripts, as well as for the entire data set in the main phase of thematic analysis.

To code the initial pair of transcripts, the anonymised texts were uploaded to NVIVO 11. The aim was to create codes from the data rather than from an existing framework, and so an inductive approach was adopted, similar to that described by Strauss and Corbin (1990), where data is reviewed line by line or in paragraphs to generate labels which grow and adapt and can then change to more abstract concepts as several instances are identified.

To begin coding the initial transcripts, the step of 'generalising initial codes' commenced using NVIVO 11, where each line of the transcript was reviewed and words or phrases (codes) that captured the 'essence' of that data were assigned. Codes refer to "tags of labels for assigning units of meaning to the descriptive or inferential information compiled during a study" (Miles & Huberman, 1994, p. 56). Generating initial codes involved identifying a feature of the data which the analyst felt was interesting or relevant and grouping them in meaningful ways. Additionally, coding to multiple codes was permitted, so an item of data did not have to be exclusively assigned to a single code. Initial codes are mostly descriptive of the data, which is separate from the process of identifying themes, which involves interpreting data and are often broader.

This process is accompanied by the constant comparative method (Charmaz, 2006), which involves comparing codes for similarities and differences, comparing codes earlier and later on in the data, and comparing, merging or fracturing data as you refine the codes at each stage of analysis.

The ‘searching for themes’ step involved organising the codes found at the initial coding stage, examining context, and meaning behind them and identifying repeating patterns in the data. Theoretical and topical knowledge was used in searching for themes to look deeper into the data to develop groupings and patterns. In this stage, hierarchical coding also took place, where codes were organised into ‘parent’ and ‘child’ codes of each other to reflect their interconnectedness or conceptual relationship. Mind maps were used to help visualise the themes and their relationships to each other (Appendix MM), as recommended by Braun and Clarke (2006).

After searching for themes across the transcripts, a selection of themes and sub-themes were identified, which were then examined more closely again and compared to look for similarities, differences, and relationships. Following was the ‘reviewing themes’ stage, which involved ongoing analysis to refine the specifics of each theme, assessing the evidence for the existence of each theme (how much data is coded to them) and generating clear definitions and names. ‘Refining and naming themes’ continued to finalise theme names and descriptions as accurately as possible to define the ‘essence’ of what each theme expressed (Braun & Clarke, 2006).

The transcripts were coded by two researchers and the final codes were compared, with detailed notes taken on the differences and similarities (Appendix NN). Codes from both researchers were found to be similar with expected differences in wording. After discussions on agreements and disagreements, the two sets of codes were merged, refined, and revised to reflect a cohesive set (Appendix OO). This served as a check-coding method (Miles & Huberman, 1994), to check whether the codes were reflected in the data, that they were being applied consistently and to sharpen their definitions.

3.4.8.6.1.2 Phase 2: Inter-rater reliability

Code checking between researchers allows more definitional clarity and serves as an initial reliability check (Miles & Huberman, 1994). After settling on a set of codes agreed between two researchers, a third researcher was enlisted to code the same pair of transcripts. The third researcher was a PhD candidate under the same supervisor but of a different research and educational background. His distance from the project was thought to be beneficial for the refinement of the codes and to bring a new perspective to the process. This researcher was given the set of codes refined previously as an NVIVO file and a detailed and revised codebook. Meetings were held to discuss and clarify this information. The third researcher was advised that although there were codes already set up ready to use, they should, if they felt it necessary, create their own codes or edit them as they saw fit, to reflect the data.

After receiving the coded transcripts from the third researcher, a measure of inter-rater reliability (IRR) was used to assess the amount of agreement between both sets of coding. Initially, the IRR measure used was the coding comparison query available as a feature of NVIVO, which takes the coding of two different users and compares the agreement and disagreements in the coding to create a percentage and Kappa Coefficient measure. However, this method yielded a low Kappa Coefficient. Comparing both sets of coding in detail, it was found that NVIVO would only compare the exact highlighting of the text by both users for each code, which was often not identical, despite intending to code the same piece of information to the same codes. This therefore gave an inaccurate measure of agreement. Differences in the unitisation of coded text in calculating reliability is a difficulty that has been documented (Campbell, Quincy, Osserman, & Pedersen, 2013) and so to remedy this, a manual method of calculating IRR was used to more accurately capture agreements and disagreements in coding excerpts of the text. The manual method was developed by McAlister et al. (2017), who aimed to create a process which could accelerate or standardize IRR practices in qualitative studies without the use of specialised software. McAlister et al. (2017) chose the calculation of IRR by Miles and Huberman (1994) over others (such as Cohen's Kappa, Scott's Pi, or Krippendorff's Alpha), which is a measure of proportional agreement, as shown in Figure 19.

Figure 19: Reliability formula by Miles and Huberman (1994)

$$\text{reliability} = \frac{\text{number of agreements}}{\text{number of agreements} + \text{disagreements}}$$

Although a proportional agreement method of calculating IRR does not consider similarities in coding due to chance, it has also been argued that a large codebook (a large number of codes used) diminishes agreement by chance and that for qualitative analysis, which is exploratory in nature (as for this project), a proportional agreement is acceptable (Kurasaki, 2000). It is for these reasons that the proportional agreement method was deemed acceptable for the manual IRR calculation for the interview data.

McAlister et al. (2017) used Microsoft Word for their method, where the comment function was used to tag words and phrases to codes by each researcher and agreements and disagreements could be totalled and inputted into the formula. Using this method, the transcripts were coded in Word using the existing NVIVO coding (and coding stripe function) to identify each user's selected text and code to which they attributed it to. Comments were used to identify users and their codes which were aggregated and used to calculate an IRR percentage agreement. Across the two transcripts, a percentage agreement of 30% was found. Miles and Huberman (1994) stated that inter-rater agreement should approach 90%, depending on the size and range of the coding scheme. Although the coding scheme was large at this stage, this percentage agreement was not acceptable.

It is possible that the difference in knowledge of the subject was detrimental to the rate of agreement, as the transcripts did involve some biological knowledge, of which the other research had little experience. Additionally, the third researcher was a novice at coding and using NVIVO, so lack of experience in these techniques could have accounted for some disagreements.

To remedy this, a fourth researcher, experienced in both the subject knowledge and coding, was recruited to code the two transcripts. IRR was calculated again using the technique mentioned above and a percentage agreement of 50% was found. This percentage agreement was again lower than the approximate 90% suggested by Miles and Huberman (1994), however, after comparing and discussing the codes with the fourth researcher, it was found that some disagreements were due to me having more contextual knowledge of the experiment and activities discussed in the interviews. Additionally, using these discussions as a code-check, some codes were refined, additional codes were identified, and some descriptions were found to need sharpening. Due to these issues, another method of assessing IRR was adopted: negotiated agreement.

Negotiated agreement is a method of testing the reliability of coding between multiple researchers. This involves comparing codes, discussing disagreements and negotiating a reconciliation of these disagreements to resolve as many as possible until a final version is created (Campbell et al., 2013) .This method may increase the reliability of coding in transcripts as it helps refine the coding scheme and control for simple errors caused by differences in knowledge or misinterpretation, (Garrison, Cleveland-Innes, Koole, & Kappelman, 2006). This makes negotiated agreement advantageous to exploratory research such as this, where new insights are of interest. Although negotiated agreement is not identical to an IRR calculation, as discussed previously, a negotiated agreement measure of reliability was well suited to this research as it was exploratory in nature (new insights were of primary interest) and there were several coding disagreements caused by different levels of knowledge between researchers.

During negotiated agreement, disagreements were discussed between the fourth researcher and I, where they were explored and built upon to develop and sharpen codes. Where information or context was missing, resulting in a disagreement, context was provided by the more knowledgeable party and the codes re-assessed. This process of discussion about codes and disagreements allowed the development of more nuanced and useful categories (Flick, 2013).

As noted above, before negotiating discrepancies, we had achieved 50% IRR. After negotiating discrepancies, we reached a 90% inter-rater agreement. We reconciled 96% of our initial disagreements. Of these disagreements, I deferred to the fourth researcher 16% of the time and the fourth researcher deferred to myself 79% of the time. A possible issue with this method involves the interpersonal dynamics between the fourth researcher and I, who is a knowledgeable professor. There was a danger that this dynamic could have affected the negotiations. However, in this negotiation, although the fourth researcher was knowledgeable in biology and coding, I was more knowledgeable on the specific subject matter in the interview. Additionally, 3% of the differences were not reconcilable in the negotiations.

Through negotiated agreement, a reasonable percentage of agreement of 90% was found (Miles & Huberman, 1994). For this project, I was the single coder for the remainder of the transcripts. Other researchers have stated that high values of inter-rater agreement justify the choice of a single coder as long as the final coder is the one whose coding was favourable during the negotiating process (Campbell et al., 2013). As the fourth researcher found my coding favourable in the negotiation most frequently, this suggests that being the single coder for the remainder of the data set in this case was acceptable.

The high inter-rater agreement suggests that a level of reliability could be inferred in the coding process and that I could be reasonably confident that my coding alone would be consistent with that of other coders, if they were involved further in the analysis. Therefore, I was confident enough in the coding process thus far to continue onto the remaining transcripts, whilst continually referring to and comparing against the coding scheme using the comparative method (Charmaz, 2006) mentioned in Section 3.4.6.2.

3.4.8.6.1.3 Phase 3: Main phase and thematic analysis report

After an acceptable negotiated agreement between coders was confirmed, the remainder of the interview transcripts were the uploaded into NVIVO 11, where they were coded in the same manner as described in Section 3.4.8.6.1.1. The same steps outlined by Braun and Clarke (2006) were used in the coding of the remaining interview transcripts. This began by familiarising with the data by listening to and reading the interviews whilst making notes on recurring or potentially interesting points. Initial codes were then generated by looking at the data line-by-line or by paragraph, searching for themes, reviewing new and existing themes and defining and narrowing themes using the constant comparative method (Charmaz, 2006).

Whilst searching for and reviewing themes, codes that shared a unifying point were often collapsed or clustered as coding continued. Codes were constantly compared, revised and their description updated, to present a clear guideline of what was included and excluded. A codebook (Appendix PP), with code names and an accurate description of what should be included, was consistently updated as more data was coded and a coding log (Appendix QQ) was kept using the NVIVO memo feature to keep track of the coding process. Difficulties that arose during the coding included the occurrence of overlapping codes and ambiguity of data items. As the data was coded, codes would sometimes emerge with similar or overlapping underlying features. By comparing and reviewing codes every two or three interviews, areas of similarity and overlap were identified, and codes would often be collapsed, merged, or eliminated should the code no longer represent a meaningful pattern in the data. For example, midway through coding the data, codes of ‘molecule shape and size’ and ‘membrane channels’ had been established, but as more items of data joined these codes it was apparent that these codes represented the students learning on these topics, and therefore these codes were incorporated as child codes under the ‘Learning’ parent code. Additionally, mind maps were used to lay out existing codes and highlight overlaps and relationships in a visual manner to help review and refine the coding structure during this process (Appendix MM). To address any ambiguity, code descriptions were revised and edited to portray the patterns they were describing in the data more accurately and were consulted and compared in instances of uncertainty. Names of the codes were also revised to reflect the patterns they represented more accurately. In addition, input from multiple coders was helpful in identifying ambiguous codes. For example, during the negotiated agreement (Section 3.4.8.6.1.2), the fourth researcher suggested a code on ‘focus’, which more accurately encompassed certain items of data which were more often more broadly coded to ‘comparison with regular teaching’. Implementing the ‘focus’ code was therefore beneficial as it helped to reflect the patterns more accurately in the data. Additionally, after a discussion in the negotiated meaning process, the codes ‘formulating ideas’ and ‘negotiating meaning’ were merged, allowing the description of this code to become more precise and lowering ambiguity between these overlapping features.

Section 4.3.1 will report the results of the thematic analysis on the interview transcripts and what they mean in the wider context of the project. Firstly, Chapter 4 will begin by detailing the analysis and results for the quantitative data.

4 Data Analysis/Results

4.1 Introduction

Section 3.4 has so far described the design, participants, procedure, and planned analysis for the main study. This chapter will describe, in detail, the analysis of the quantitative and qualitative data collected in the main study.

4.2 Quantitative Analysis

This section reports the results of the quantitative data. This includes data from the cell knowledge test, tests of spatial ability and the test of fine dexterity. The analysis of this data aims to explore the following research questions:

1. Will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?

2. Does existing spatial ability have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?

3. Does existing fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment??

RQ1 will be explored by using the cell knowledge pre and post-test scores. The data will be explored inferentially by using a 2x3 mixed ANOVA to test for difference in test scores across time (pre-test, post-test, and retention-test) and by condition (haptic or non-haptic).

RQ2 and RQ3 will be explored by using independent t-tests to compare measures of spatial ability and fine dexterity between groups (haptic and non-haptic), and by using a mixed ANCOVA, using the measures of spatial ability and fine dexterity as covariates.

4.2.1 Exclusions

Issues in data collection required certain participants to be excluded from results. Ten participants were excluded for having less time on the system due to a technical fault, and missing cell knowledge test data due to absence. This resulted in a total of 64 participants for analysis involving the cell knowledge test.

At the retention-test stage however, absence and participants no longer attending the school resulted in ten missing retention scores, resulting in 54 participants for analysis involving retention.

One participant was found to have missed two pages of the SRT seemingly by mistake, and so was excluded from tests involving the SRT. In these instances, 63 participants were included.

4.2.2 Descriptive statistics

To initially explore the data, this section reports the descriptive statistics for the dataset. The mean scores for the pre, post and retention cell knowledge tests are displayed in Table 7.

Table 7: Means and standard deviations for pre and post-test scores in haptic and non-haptic conditions

Descriptive Statistics				
	Condition	Mean (/ 56)	Std. Deviation	N
Pre-test scores	Haptic	25.45	4.793	29
	Non-haptic	22.96	5.827	25
	Total	24.30	5.393	54
Post-test scores	Haptic	31.72	6.070	29
	Non-haptic	30.52	7.258	25
	Total	31.17	6.610	54
Retention-test scores	Haptic	28.79	7.889	29
	Non-haptic	30.60	7.343	25
	Total	29.63	7.624	54

Table 7 shows that the mean pre-test score is higher in the haptic group (M=25.45, SD=4.79) than the non-haptic group (M=22.96, SD=5.83). The mean post-test scores are higher in the haptic group (M=31.72, SD=6.07) than the non-haptic group (M=30.52, SD=7.26). Also, the retention scores were higher in the non-haptic group (M=30.60, SD=7.34) than the haptic group (M=28.79, SD=7.89).

Additionally, the overall pre-test mean scores were the lowest (M=24.30, SD=5.39), with the post-test mean scores being highest (M=31.17, SD=6.61). The overall mean retention scores were positioned between the pre and post-scores (M=29.63, SD=7.62).

To test if the differences between the pre, post and retention scores were statistically significant, inferential tests were conducted. These are reported below.

4.2.2.1 Potential outliers

After exploring the data set, two potential outliers were identified in the non-haptic group for the post-test scores. Two participants scored 2.6 and 2.8 standard deviations higher than others in the non-haptic group in their post-test. These two participants also worked together as a pair on the haptic device.

Although these scores were identified by SPSS as outliers, they were not identified as extreme values (>3 SD away from the mean). These scores were also not identified as outliers when included in the entire data set, which includes the haptic and non-haptic group. Additionally, these participants' pre-tests scores were not identified as outliers and the data is generally normally distributed (see the Kolmogorov-Smirnov test in Section4.2.5), suggesting that the larger values do not have a significant impact on the overall dataset.

Due to these reasons (and because analysis conducted with the outliers removed revealed no changes to the significance of the ANOVA and ANCOVA test to follow), it was decided that it was not justifiable to remove these two participants from analysis. However, it is an interesting case to note that these two participants working together both scored more highly than others and did not score significantly higher that others in any other measure. The reason these participants scored more highly pre-test than others in the non-haptic group could lie in analysis beyond the scope of this thesis (e.g. video analysis of their collaboration or interactions may be insightful). However, as this investigation was outside the scope of this thesis, it is not addressed here and is instead noted for possible future research.

4.2.3 One-way ANOVA for differences between condition for pre, post, and retention-test scores

To test whether the pre-test, post-test and retention-test scores were significantly different between groups, a one-way ANOVA was conducted.

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F = .057$, $p=.81$), post-test ($F=.04$, $p=.84$) and retention ($F=.12$, $p=.726$) scores.

The one-way ANOVA showed that there were no significant differences in the pre-test scores for haptic ($M=25.19$, $SD=5.40$) and non-haptic ($M=22.56$, $SD=5.82$) conditions; $F(1,62)=3.45$, $p=.066$. There was no significant difference in the post-test scores for haptic ($M=31.25$, $SD=6.03$) and non-haptic ($M=30.69$, $SD=6.68$) conditions: $F(1, 62)=.13$, $p=.73$.

There were also no significant differences in the retention scores between haptic ($M=28.79$, $SD=7.89$) and non-haptic conditions ($M=30.60$, $SD=7.34$): $F(1, 52)=.75$, $p=.39$.

This one-way ANOVA showed that the scores in the pre-test, post-test and retention-test did not differ significantly between the haptic and non-haptic groups.

To test whether scores for the individual questions of the pre-test, post-test and retention-tests were significantly different between groups, an independent samples t-test was conducted. Table 8 shows the mean pre, post and retention scores for haptic and non-haptic conditions for each question on the test of cell knowledge.

Table 8: Mean scores for each question of the pre, post and retention cell knowledge tests by condition.

Test		**Test Questions**					
	Condition	Q1 Mean Score (/35)	SD	Q2 Mean Score (/7)	SD	Q3 Mean Score (/14)	SD
Pre-test	Haptic	15.88	4.13	3.82	1.64	5.50	2.03
	Non-haptic	14.19	4.21	3.53	1.85	4.84	2.16
	Total	15.03	4.22	3.67	1.74	5.17	2.10
Post-test	Haptic	18.38	4.67	4.25	1.85	8.31	1.97
	Non-haptic	18.13	5.74	4.22	1.62	8.34	1.43
	Total	18.25	5.19	4.23	1.73	8.33	1.71
Retention-test	Haptic	17.48	7.01	4.31	1.04	7.00	2.10
	Non-haptic	18.50	6.12	4.46	1.63	7.38	1.92
	Total	17.96	6.56	4.38	1.34	7.18	2.01

Table 8 shows that for Question 1 of the cell knowledge test, the haptic group scored higher on average than the non-haptic group at both pre and post-test. At the retention-test time point however, the non-haptic group scored higher on average than the haptic group. For Question 2, the haptic group scored higher on average than the non-haptic group at pre and post-test, but the non-haptic group scored higher on average than the haptic group. For Question 3, the haptic group scored higher on average than the non-haptic group at pre-test, but for the post and retention-tests, the non-haptic group scored higher on average than the haptic group.

To determine whether differences between conditions for each question at each time-point were statistically significant, independent samples t-tests were conducted. Levene's test showed the assumption of homogeneity of variance was met in each case ($p>.05$) except for Question 2 of the retention test ($F =10.04$, $p=.003$), for which the "equal variances not assumed" statistics were used.

There were no significant differences found between haptic and non-haptic conditions for any questions at any time point. This included Question 1 at pre-test ($t(62)=2.62$, $p=.11$), post ($t(62)=.04$, $p=.85$) or retention-test ($t(53)=.33$, $p=.57$), Question 2 at pre-test ($t(62)= .42$, $p=.52$), post-test ($t(62)=.005$, $p=.94$) or retention-test ($t(41.59)=.17$, $p=.69$), or Question 3 at pre-test ($t(62)=1.57$, $p=.22$), post-test ($t(62)=.005$, $p=.94$) or retention-test ($t(53)=.50$, $p=.84$). The independent samples t-tests showed that there were no significant differences between conditions for any question of the cell knowledge test at pre, post or retention time points.

The following Section (4.2.4) will test any statistical significance of the differences in pre, post and retention-test scores according to gender/school.

4.2.4 One-way ANOVA for differences between pre, post, and retention-test scores according to gender/school

To test whether the pre-test, post-test and retention-test scores were significantly different according to gender (and consequently school, as single sex schools were used in this study), a one-way ANOVA was conducted.

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F = 3.50$, $p=.07$), post-test ($F=.13$, $p=.73$) and retention-test ($F=.75$, $p=.39$) scores.

The one-way ANOVA showed that there were significant differences in the pre-test scores for males ($M=21.74$, $SD=5.07$) and females ($M=25.88$, $SD=5.65$) ($F(1,62)= 9.47$, $p=.003$), but no significant differences in the post-test scores for males ($M=29.97$, $SD=6.18$) and females ($M=31.91$, $SD=6.39$) ($F(1,62)=1.52$, $p=.22$). However, there were significant differences in the retention scores for males ($M=25.74$, $SD=6.02$) and females ($M=33.52$, $SD=7.13$): $F(1,62)=18.76$, $p=<.001$. This ANOVA showed that the scores in the pre-test and retention-test differed significantly between males and females. However, there were no significant differences between males and females in the post-test scores.

The results of this ANOVA show that the male students had a lower level of knowledge on the topic of cell biology before the intervention than females, but learned more during the intervention, reaching average scores comparable to those of the female students at post-test. By the retention time-point however, males again showed a significantly lower knowledge score than females on average. It is possible that if the male students learned more during the same time period than female students, they may have been exposed to a higher cognitive load, which according to CLT (Sweller, 1994) could affect the ability of those students to process information into long term memory (Section 2.4.2.2). It may be expected then, that students who were exposed to more new information during the intervention may not retain that information as successfully. Additionally, the results of this ANOVA regarding the retention tests should be treated with caution, as a potential limitation to this study was the long interval between the post and retention-tests (discussed in Section 5.7).

Although this ANOVA showed significant gender differences for the pre and retention-test scores, subsequent analysis shows that this finding does not have an effect on the ability to answer the research questions of this study. This is reported and discussed further in Section 4.2.5.3.

The following Section (4.2.5) will go on to test the statistical significance of the difference in pre, post and retention scores, and any effects of the condition (haptic or non-haptic) on the change in those scores.

4.2.5 Mixed ANOVA for pre, post and retention-test scores

4.2.5.1 Assumptions

A Kolmogorov-Smirnov test showed that the data did not deviate from normality ($p>0.05$). The assumption of normality was met.

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F =.057$, $p=.81$), post-test ($F=.04$, $p=.84$) and retention ($F=.12$, $p=.726$) scores. Mauchly's test also indicated that the assumption of sphericity was met: $\chi2(2)=84$, $p=.66$).

4.2.5.2 ANOVA

With assumptions met, a mixed ANOVA was conducted. A significant main effect of time was found: $F(1,104)=26.56$, $p<0.001$. This shows that across time points (pre, post and retention) there was a significant difference in knowledge test scores. Post-hoc tests using the Bonferroni correction indicated that the mean score for the pre-tests ($M=24.30$, $SD=5.83$) was significantly different than the mean score of the post-tests ($M=31.17$, $SD=6.61$) ($p=<.01$) and the retention scores ($M=29,63$, $SD=7.62$) ($p<.01$). There was no significant difference between the means of post-test and retention scores ($p=.50$). Examining the means, participants scored higher after using system and retained that knowledge, as there was no difference between post and retention scores.

However, there was no significant interaction effect of condition: $F(2, 104)=2.42$, $p=.09$. This means that the condition did not affect the influence of time on scores. Therefore, whether the participants were in the haptic or non-haptic condition did not affect the change in scores over time.

4.2.5.3 ANOVA to determine any interaction effects of gender

The one-way ANOVA reported in Section 4.2.4 showed that in the overall sample, the scores in the pre-test and retention-test differed significantly between males and females.

To determine whether these gender differences had any interaction with the effects of condition on the change in scores over time, a mixed ANOVA was conducted. As reported in Section 4.2.5.2, a significant main effect of time was found: $F(2,100)=28.82$, $p<0.001$ and there was no significant interaction effect of condition: $F(2, 100)=2.75$, $p=.07$. There was a significant interaction effect between time and gender: $F(2, 100)=3.92$, $p=.02$, but there was no significant interaction effect between time, condition, and gender $F(2, 100)=.48$, $p=.62$. Therefore, although there is a significant difference between genders on the pre and retention-test scores (Section 4.2.4), gender did not significantly interact with the effect of condition on the change in scores over time.

The research questions in this study concern the effect of condition (haptic or non-haptic) on the change in scores over time (knowledge gain between pre, post and retention-tests). Therefore, as this ANOVA shows that gender differences at pre and retention-test within the sample do not interact with the effect of condition on the change in scores over time, the results of the ANOVA and ANCOVA used to answer the research questions in this study are not affected.

4.2.6 Mixed ANCOVA for pre, post and retention scores

The Mixed ANOVA in Section 4.2.5 revealed a significant main effect of time, but no significant interaction effect with condition. To control for the possible covariates of spatial ability and fine dexterity, a mixed analysis of co-variance (ANCOVA) was conducted.

As the covariates used in this study were constant (did not change across time points), the covariate scores were centred before being entered into the ANCOVA (Van Breukelen & Van Dijk, 2007), as this allows the within subjects factor sum of squares to be unaltered in the presence of the covariate.

Mixed ANCOVAs were conducted to determine any statistically significant covariate effects of spatial ability or fine dexterity on changes in score across pre, post and retention-tests. Separate ANCOVAs were conducted for each covariate. Covariates used were BDT score, SRT score, combined spatial score, fine dexterity finger score, fine dexterity tweezer score and fine dexterity combined score. Each ANCOVA will be reported below.

4.2.6.1 BDT ANCOVA

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F=1.33$, $p=.25$), post-test ($F=.01$, $p=.92$) and retention-test ($F=.02$, $p=.90$) scores. Mauchly's test also indicated that the assumption of sphericity was met: $\chi2(2)=.72$, $p=.69$).

There was a significant effect of time ($F(2,100)=25.69$, $p=<.001$), meaning that scores differed significantly across time points. There was no significant interaction effect of condition (haptic or non-haptic) ($F(2,100)=2.00$, $p=.14$), meaning that condition did not significantly affect change in scores across time. There was also no significant interaction effect of the covariate (BDT) ($F(2,100)=.16$, $p=.85$), meaning that BDT score did not significantly affect the change in scores over time. Additionally, the variance of BDT scores was 45.95, with a range of 27 (minimum value 22, maximum value 49), suggesting a large variance of scores spread from the mean.

4.2.6.2 SRT ANCOVA

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F=.67$, $p=.42$), post-test ($F=.02$, $p=.88$) and retention ($F=.12$, $p=.73$) scores. Mauchly's test also indicated that the assumption of sphericity was met: $\chi2(2)=.94$, $p=.63$).

There was a significant effect of time ($F(2,100)=24.65$, $p=<.001$), meaning that scores differed significantly across time points. There was no significant interaction effect of condition (haptic or non-haptic) ($F(2,100)=2.28$, $p=.11$), meaning that condition did not significantly affect change in scores across time. There was also no significant interaction effect of the covariate (SRT) ($F(2,100)=.48$, $p=.62$), meaning that SRT scores did not significantly affect the change in scores over time. Additionally, the variance of SRT scores was 18.75, with a range of 19 (minimum value 28, maximum value 47), suggesting a large variance of scores spread from the mean.

4.2.6.3 Combined spatial score ANCOVA

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F=.1.21$, $p=.28$), post-test ($F=.002$, $p=.96$) and retention-test ($F=.004$, $p=.95$) scores. Mauchly's test also indicated that the assumption of sphericity was met: $\chi2(2)=.81$, $p=.67$).

There was a significant effect of time ($F(2,100)=24.23$, $p=<.001$), meaning that scores differed significantly across time points. There was no significant interaction effect of condition (haptic or non-haptic) ($F(2,100)=1.88$, $p=.16$), meaning that condition did not significantly affect change in scores across time. There was also no significant interaction effect of the covariate (combined spatial score) ($F(2,100)=.30$, $p=.74$), meaning that combined spatial score did not significantly affect the change in scores over time. Additionally, the variance of combined spatial ability score was 80.02, with a range of 43 (minimum value 50, maximum value 93), suggesting a large variance of scores spread from the mean.

4.2.6.4 Fine dexterity finger score ANCOVA

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F=.94$, $p=.34$), post-test ($F=.18$, $p=.67$) and retention-test ($F=.06$, $p=.80$) scores. Mauchly's test also indicated that the assumption of sphericity was met: $\chi2(2)=.01$, $p=1.00$).

There was a significant effect of time ($F(2,100)=28.73$, $p=<.001$), meaning that scores differed significantly across time points. There was no significant interaction effect of condition (haptic or non-haptic) ($F(2,100)=1.97$, $p=.15$), meaning that condition did not significantly affect change in scores across time. However, there was a significant interaction effect of the covariate (fine dexterity finger score) ($F(2,100)=6.37$, $p=.002$), meaning that the fine dexterity finger scores significantly affected the change in scores over time.

However, when running a 2x2 mixed ANCOVA including the pre and post scores only and using the fine dexterity finger score as the covariate, no interaction effect of the covariate is found: ($F(1,60)=1.00$, $p=.75$). This suggests that the influence the fine dexterity finger score as a covariate lies in the difference between the post-intervention and retention time points.

To explore this further, Pearson's r correlational analyses were conducted testing for: 1) any correlation between the score difference between pre and post-tests and finger fine dexterity, and 2) any correlation between post and retention-test scores and finger fine dexterity. Results of the Pearson r correlation indicated that there was a significant negative association between score difference from post to retention-tests and finger fine dexterity, ($r(51)=.-.37$, $p=.006$). However, there was no significant association between score difference from pre to post-test and finger fine dexterity ($r(61)=.06$, $p=.67$). These results in addition to the ANCOVA suggest that the association between finger fine dexterity and change in tests scores originates from the difference between post-intervention and retention scores. Therefore, finger fine dexterity was not shown to significantly affect the change in scores from pre to post-intervention but was shown to affect the retention of the knowledge they had gained.

4.2.6.5 Fine dexterity tweezer score ANCOVA

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F=1.31$, $p=.26$), post-test ($F=.082$, $p=.78$) and retention ($F=.12$, $p=.75$) scores. Mauchly's test also indicated that the assumption of sphericity was met: $\chi2(2)=.78$, $p=.68$).

There was a significant effect of time ($F(2,100)=25.84$, $p=<.001$), meaning that scores differed significantly across time points. There was no significant interaction effect of condition (haptic or non-haptic) ($F(2,100)=1.86$, $p=.16$), meaning that condition did not significantly affect change in scores across time. There was also no significant interaction effect of the covariate (finger dexterity tweezer score) ($F(2,100)=.84$, $p=.44$), meaning that finger dexterity tweezer score did not significantly affect the change in scores over time.

4.2.6.6 Fine dexterity combined score ANCOVA

Levene's test showed the assumption of homogeneity of variance was met for the pre-test ($F=1/07$, $p=.31$), post-test ($F=.10$, $p=.75$) and retention ($F=.08$, $p=.77$) scores. Mauchly's test also indicated that the assumption of sphericity was met: $\chi2(2)=.27$, $p=.88$).

There was a significant effect of time ($F(2,100)=26.63$, $p=<.001$), meaning that scores differed significantly across time points. There was no significant interaction effect of condition (haptic or non-haptic) ($F(2,100)=1.66$, $p=.20$), meaning that condition did not significantly affect change in scores across time. There was a significant interaction effect of the covariate (fine dexterity combined score) ($F(2,100)=3.39$, $p=.04$, $\eta^2=.06$), meaning that finger dexterity combined score was shown to significantly affect the change in scores over time. However, as the combined score is a combination of the finger and tweezer tests, and the ANCOVAs shown previously (Sections 4.2.6.4 and 4.2.6.5) have established that there was a significant effect of the finger score but not for the tweezer score, the significance of the combined score can be attributed to the finger portion of the Morrisby Fine Dexterity test.

4.2.6.7 ANCOVA Summary

The interaction effects between condition and knowledge scores across pre-intervention, post-intervention and retention tests were non-significant and the main effect of time was significant regardless of covariates. Overall, controlling for spatial ability was not shown to significantly alter the effect of condition on the differences in test scores across all time points. However, the finger portion of the fine dexterity test was shown to be a covariate in the interaction between condition and knowledge test scores and subsequent correlational analysis suggests that this interaction lies in the retention of knowledge (score changes between post-intervention and retention). There was no interaction effect found for the tweezer portion of the fine dexterity test. A significant interaction with the combined fine dexterity score was found, although this can be attributed to the significant interaction effect of the finger portion of the test. Therefore, of the possible covariates explores using mixed ANCOVAs, only the finger fine dexterity scores have shown a significant interaction effect, suggesting that finger fine dexterity had an effect in the retention of knowledge in this study.

4.2.7 Cell knowledge test true/false/unsure section answer changes

So far, this chapter has explored the cell knowledge test scores and how they differ across pre-intervention, post-intervention, and retention tests. Using the overall cell knowledge test scores, the mixed ANOVA showed a significant increase in scores from pre-intervention to post-intervention (Section 4.2.3). To explore the learning gains in more detail, each statement in the true/false/unsure section of the cell knowledge test was examined and changes in answers from pre- to post-intervention were explored. In this section, each statement will be identified and how the participants changed their answers from pre- to post-intervention will be discussed.

Although the ANOVA showed that students increased their cell knowledge score from pre to post-intervention, it could not provide more detail on which concepts may have been affected by the intervention and to what extent. A more detailed analysis into the true/false/unsure section of the cell knowledge test allowed further exploration into how students' knowledge changed from pre- to post-intervention. Each statement in the true/false/unsure section corresponded with the understanding of certain concepts regarding the cell membrane and therefore an analysis of how students answered each statement both before and after the intervention was conducted to gain insight into the learning or lack of learning in those concepts. A table summarising each statement and the corresponding concepts can be seen in Appendix SS.

Answers from the tests were categorised into correct, incorrect, or unsure. Changes from pre- to post-intervention were categorised according to whether the participants answered correctly, incorrectly, or as unsure in the pre and post-intervention tests. Table 9 details the categories and their definitions.

Table 9: Answer change categories and their definitions

Category	**Definition**
None-correct	No change. In the pre and post-test, the answer was correct.
None-incorrect	No change. In the pre and post-test, the answer was incorrect.
None-unsure	No change. In the pre and post-test, the participant answered 'unsure'.
Correct to incorrect	There was a change in answer pre to post-test. The pre-test answer was correct, but post-test the answer was incorrect

Incorrect to correct	There was a change in answer pre to post test. The pre-test answer was incorrect, but post-test the answer was correct
Unsure to correct	There was a change in answer pre to post test. Pre-test the participant answered 'unsure', but post-test the answer was correct.
Unsure to incorrect	There was a change in answer pre to post test. Pre-test the participant answered 'unsure', but post-test the answer was incorrect.

By using the frequencies of students whose answer changes corresponded with the categories in Table 9, it was possible to make a visual representation of how students' answers changed from pre- to post-intervention. These visual representations can be seen below from Figure 20 to Figure 46, which show a bar graph for each statement in the true/false/unsure section of the cell knowledge test depicting how the sample changed their answers from pre- to post-intervention.

4.2.7.1 Statement 1: The cell membrane is a barrier that stops everything from entering /leaving the cell

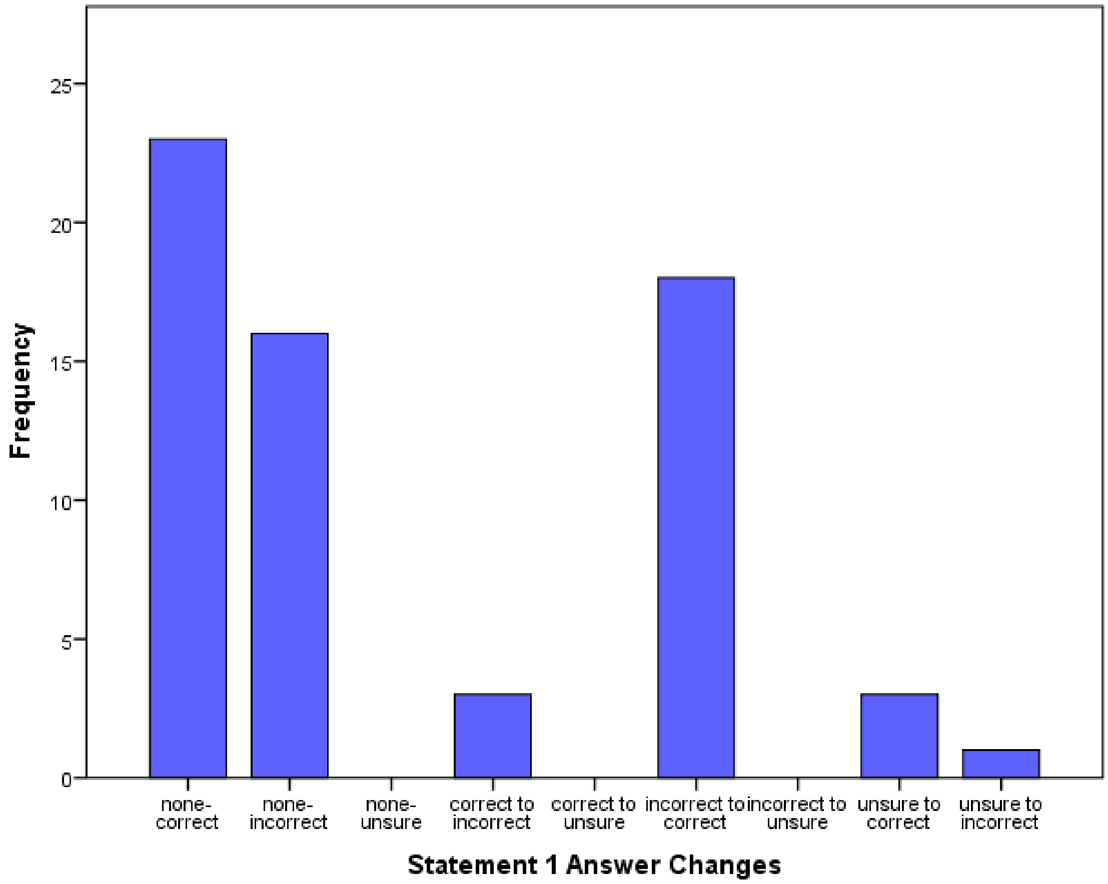


Figure 20: Bar chart depicting answer changes for Statement 1 on the pre and post-intervention cell knowledge tests

Statement 1 refers to the selective permeability of the membrane. For this statement, the answer change categories in order of frequency are shown in Table 10.

Table 10: Answer change categories for Statement 1 including frequency and percentage of sample

Category	Number of students	% of sample
None-correct	23	36%
Incorrect to correct	18	28%
None-incorrect	16	25%
Correct to incorrect	3	5%
Unsure to correct	3	5%
Unsure to incorrect	1	2%

For Statement 1, 36% showed correct knowledge of this topic before and after the intervention. 28% changed their incorrect answer at pre-intervention to a correct answer post-intervention, but 25% answered incorrectly both pre- and post-intervention.

4.2.7.1.1 Haptic and non-haptic comparison for Statement 1

The answer changes for Statement 1 were also compared between haptic and non-haptic conditions, which are shown in Figure 21.

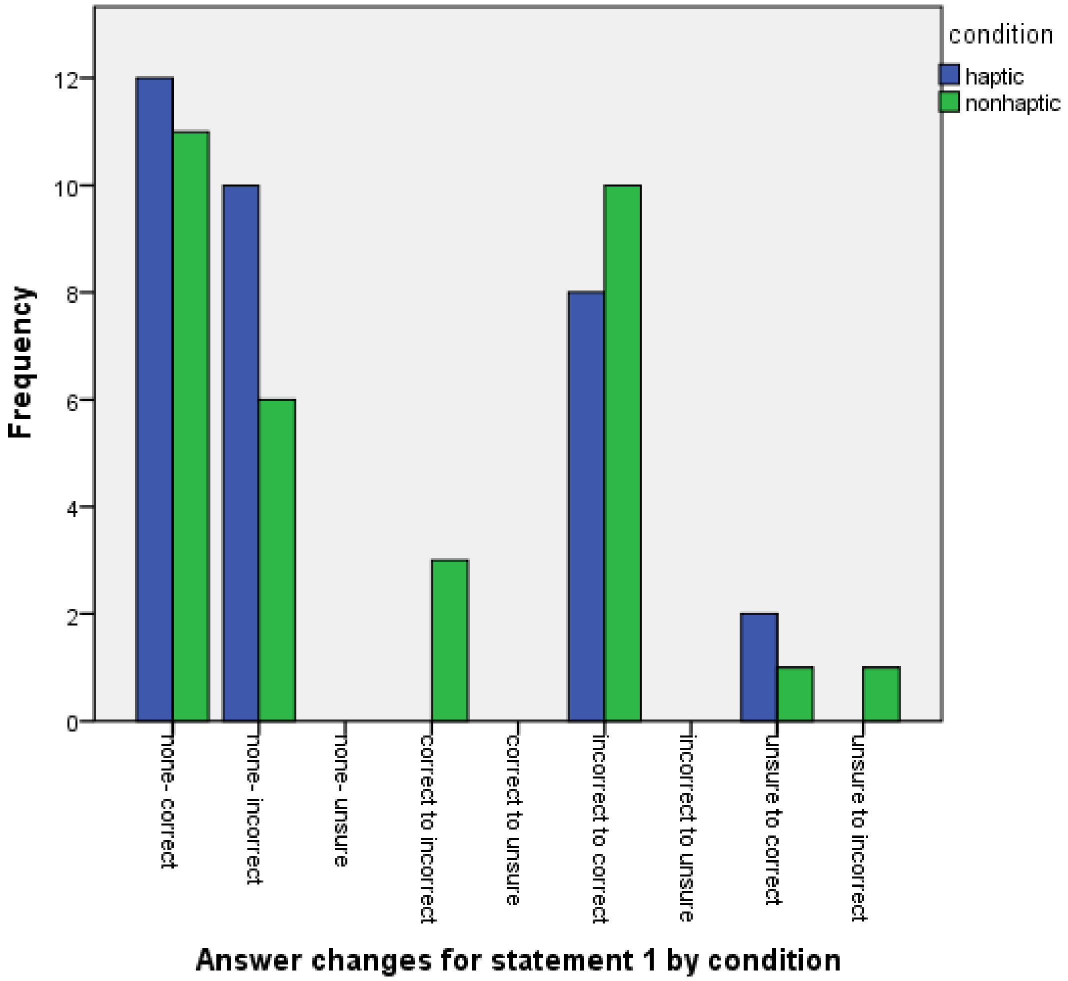


Figure 21: Clustered bar graph of answer changes for Statement 1 separated by condition

Frequencies for each answer change category for Statement 1 separated by haptic and non-haptic conditions can be seen in Table 11.

Table 11: Answer change conditions for Statement 1-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	12	11
None-incorrect	10	6

Incorrect to correct	8	10
Correct to incorrect	0	3
Unsure to correct	2	1
Unsure to incorrect	0	1

4.2.7.2 Statement 2: The cell membrane is fluid

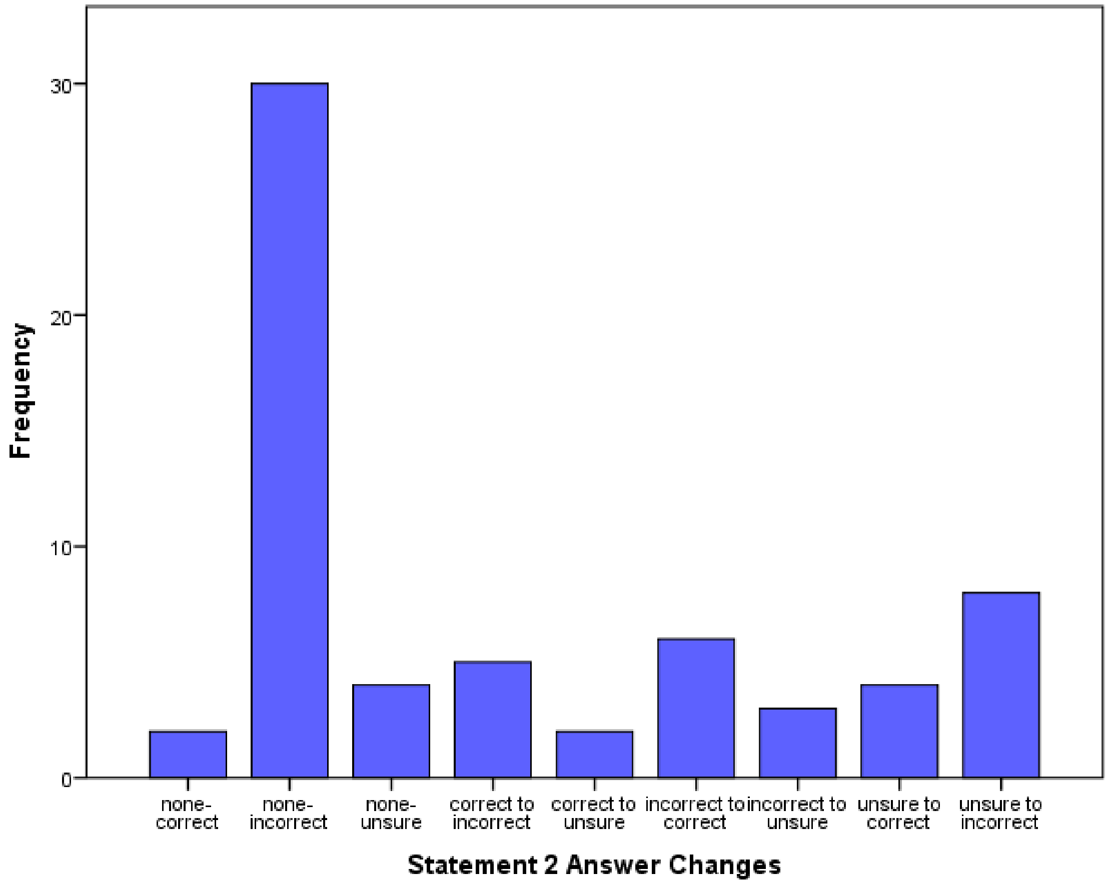


Figure 22: Bar chart depicting answer changes for Statement 2 on the pre- and post-intervention cell knowledge tests

This statement refers to the fluidity of the membrane. For this statement, the answer change categories in order of frequency are shown in Table 12.

Table 12: Answer change categories for Statement 2 including frequency and percentage of sample

Category	**Number of students**	**% of sample**
None-incorrect	30	47%
Unsure to incorrect	8	13%
Incorrect to correct	6	9%

Correct to incorrect	5	8%
None-unsure	4	6%
Unsure to correct	4	6%
Incorrect to unsure	3	5%
Correct to unsure	2	3%

For Statement 2, the most frequent answer change category was no change with incorrect answers both pre- and post-intervention for 47% of the sample. Subsequent categories show little variance in frequency.

4.2.7.2.1 Haptic and non-haptic comparison for Statement 2

The answer changes for Statement 2 were also compared between haptic and non-haptic conditions, which are shown in Figure 23.

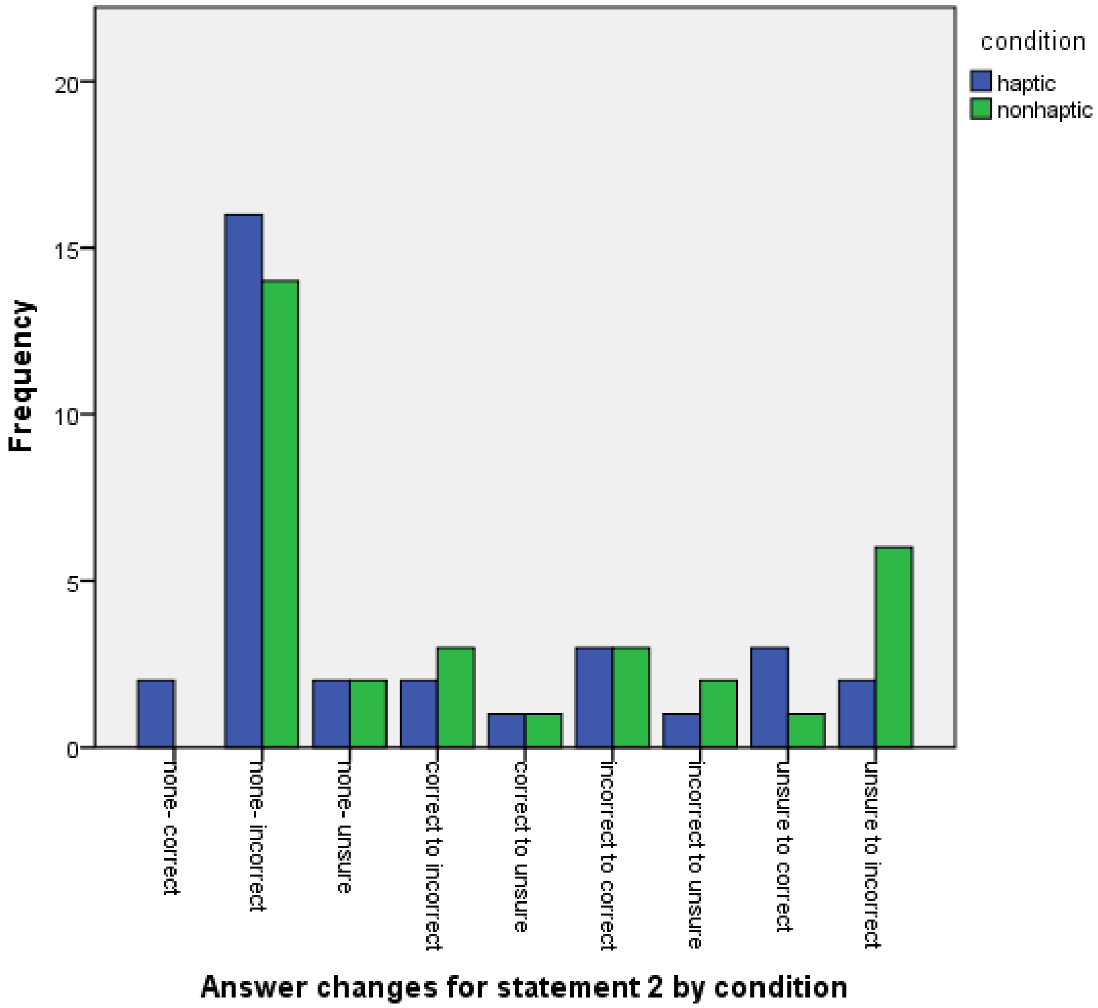


Figure 23: Clustered bar graph of answer changes for Statement 2 separated by condition

Frequencies for each answer change category for Statement 2 separated by haptic and non-haptic conditions can be seen in Table 13.

Table 13: Answer change conditions for Statement 2-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	12	11
None-incorrect	10	6
Incorrect to correct	8	10
Correct to incorrect	0	3
Unsure to correct	2	1
Unsure to incorrect	0	1

4.2.7.3 Statement 3: The cell membrane contains membrane proteins that sit in a fixed position in the membrane

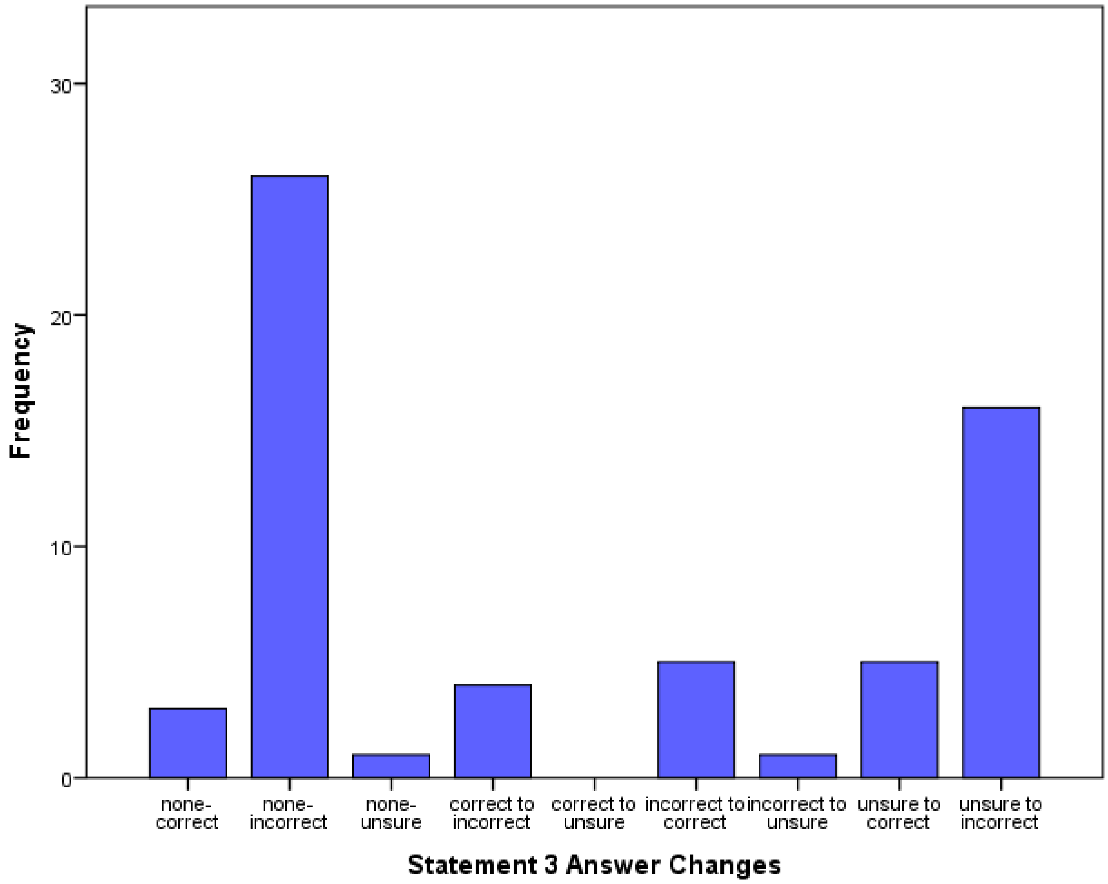


Figure 24: Bar chart depicting answer changes for Statement 3 on the pre- and post-intervention cell knowledge tests

This statement refers to membrane proteins and their movement in the fluid cell membrane. For this statement, the answer change categories in order of frequency are shown in Table 14.

Table 14: Answer change categories for Statement 3 including frequency and percentage of sample

Category	Number of students	% of sample
None-incorrect	26	41%
Unsure to incorrect	16	25%
Unsure to correct	5	8%
Incorrect to correct	5	8%
Correct to incorrect	4	6%
None-correct	3	5%

None-unsure	1	2%
Incorrect to unsure	1	2%

Most frequently, students answered incorrect both pre- and post-intervention (41%), followed by changing from unsure to incorrect (25%). The subsequent category frequencies show little variance.

4.2.7.3.1 Haptic and non-haptic comparison for Statement 3

The answer changes for Statement 3 were also compared between haptic and non-haptic conditions, which are shown in Figure 25.

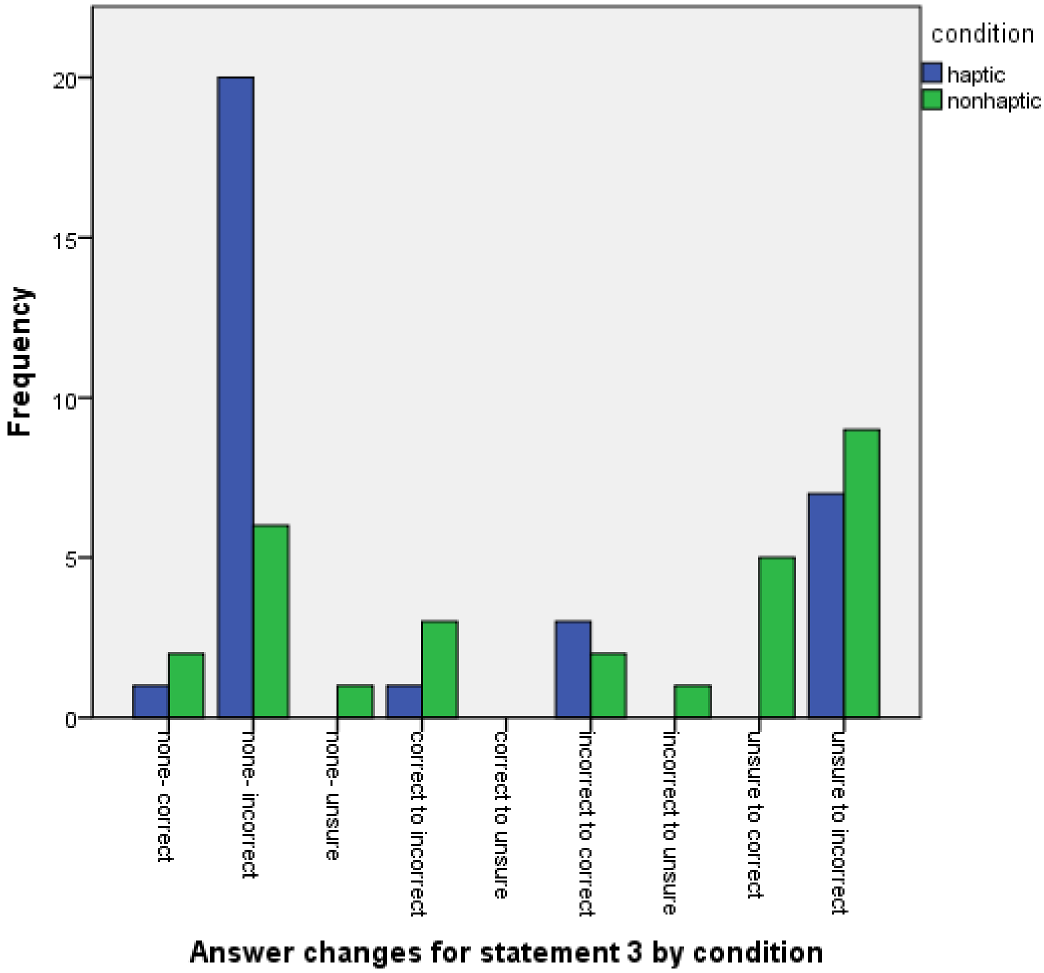


Figure 25: Clustered bar graph of answer changes for Statement 3 separated by condition

Frequencies for each answer change category for Statement 3 separated by haptic and non-haptic conditions can be seen in Table 15.

Table 15: Answer change conditions for Statement 3-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	1	2
None-incorrect	20	6
None-unsure	0	1
Correct to incorrect	3	1
Incorrect to unsure	0	1
Unsure to correct	0	5
Unsure to incorrect	7	9

4.2.7.4 Statement 4: All membrane proteins form channels that allow anything to cross the membrane and enter the cell

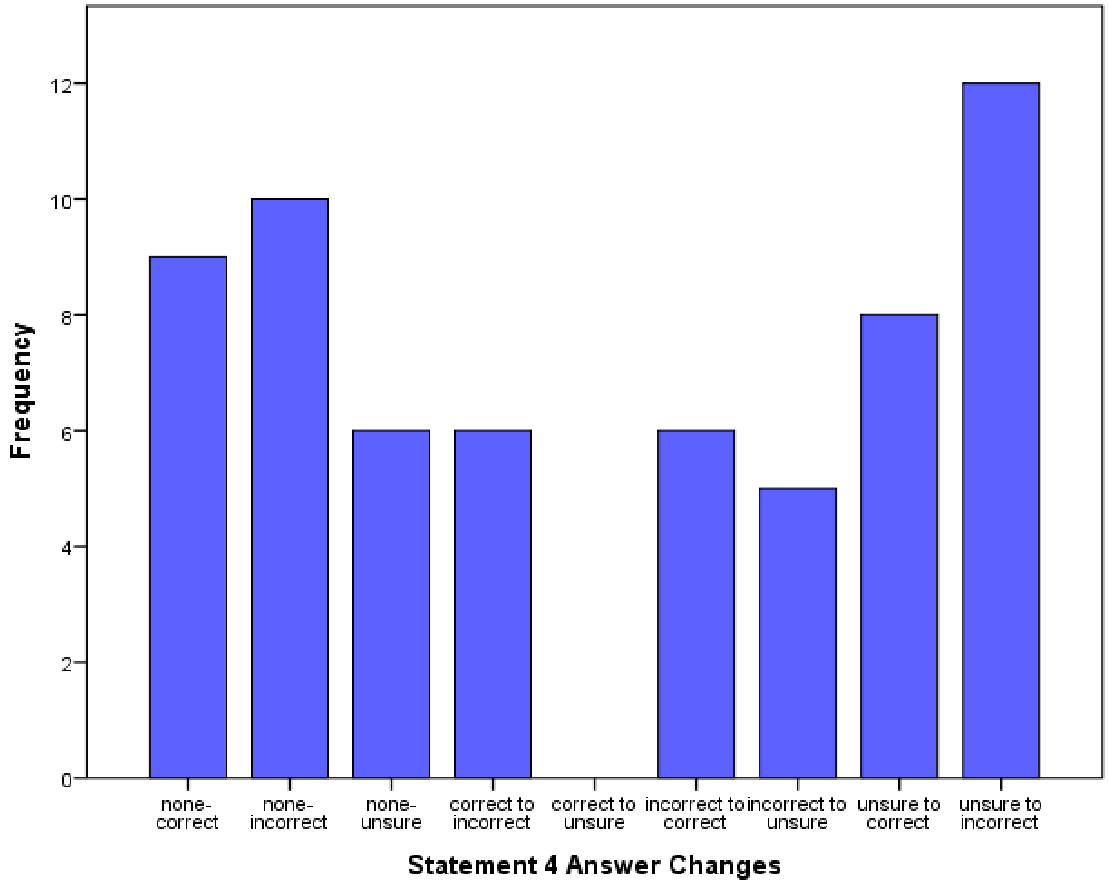


Figure 26: Bar chart depicting answer changes for Statement 4 on the pre- and post-intervention cell knowledge tests

Statement 4 refers to membrane channels/diffusion. For this statement, the answer change categories in order of frequency are shown in Table 16.

Table 16: Answer change categories for Statement 4 including frequency and percentage of sample

Category	Number of students	% of sample
Unsure to incorrect	12	19%
None-incorrect	10	16%
None-correct	9	14%
Unsure to correct	8	13%
None-unsure	6	9%
Correct to incorrect	6	9%
Incorrect to correct	6	9%
Incorrect to unsure	5	8%

Most frequently, students changed from answering ‘unsure’ pre-intervention to an incorrect answer post-intervention (19%), followed by answering incorrectly both pre- and post-intervention (16%). The subsequent category frequencies show little variance.

4.2.7.4.1 Haptic and non-haptic comparison for Statement 4

The answer changes for Statement 4 were also compared between haptic and non-haptic conditions, which are shown in Figure 27.

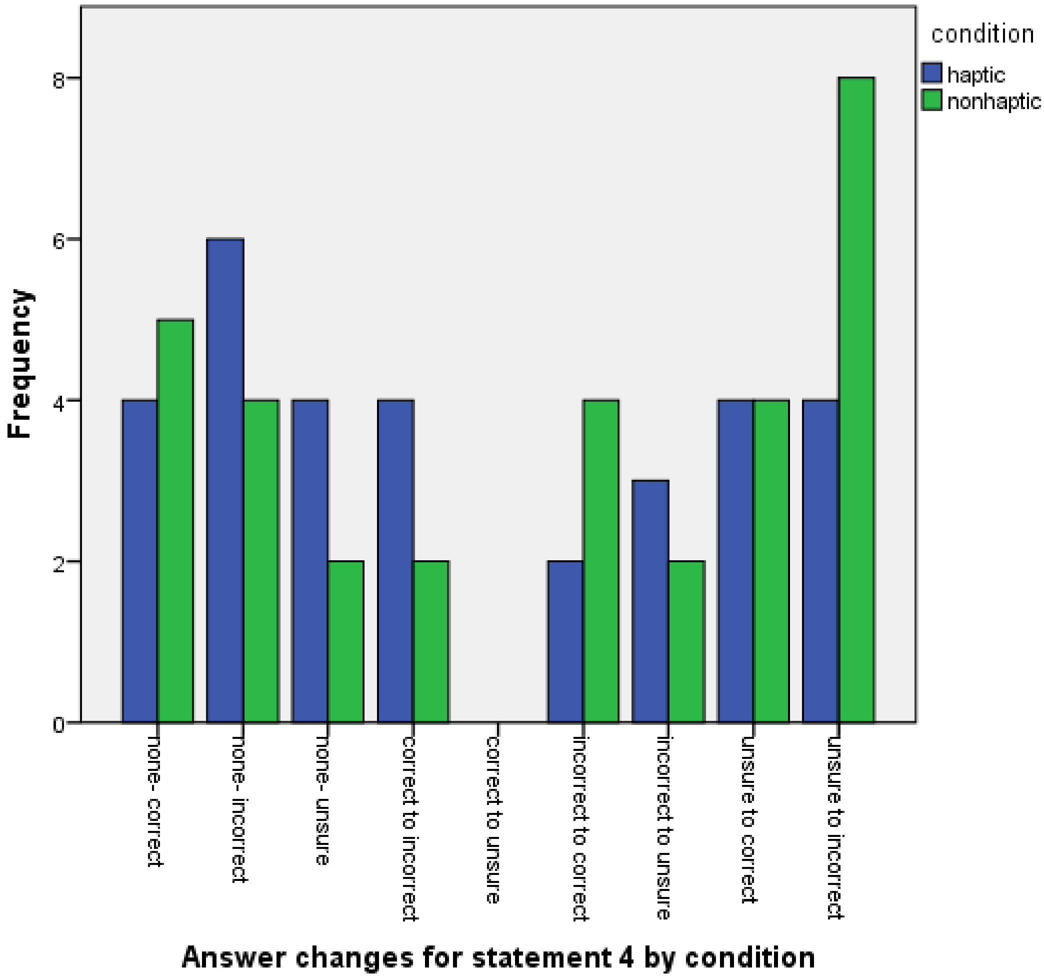


Figure 27: Clustered bar graph of answer changes for Statement 4 separated by condition

Frequencies for each answer change category for Statement 4 separated by haptic and non-haptic conditions can be seen in Table 17.

Table 17: Answer change conditions for Statement 4-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	4	5
None-incorrect	6	4
None-unsure	4	2
Correct to incorrect	4	2
Incorrect to correct	2	4
Incorrect to unsure	3	2
Unsure to correct	4	4
Unsure to incorrect	4	8

4.2.7.5 Statement 5: Oxygen can freely enter and exit a cell (does not need a channel)

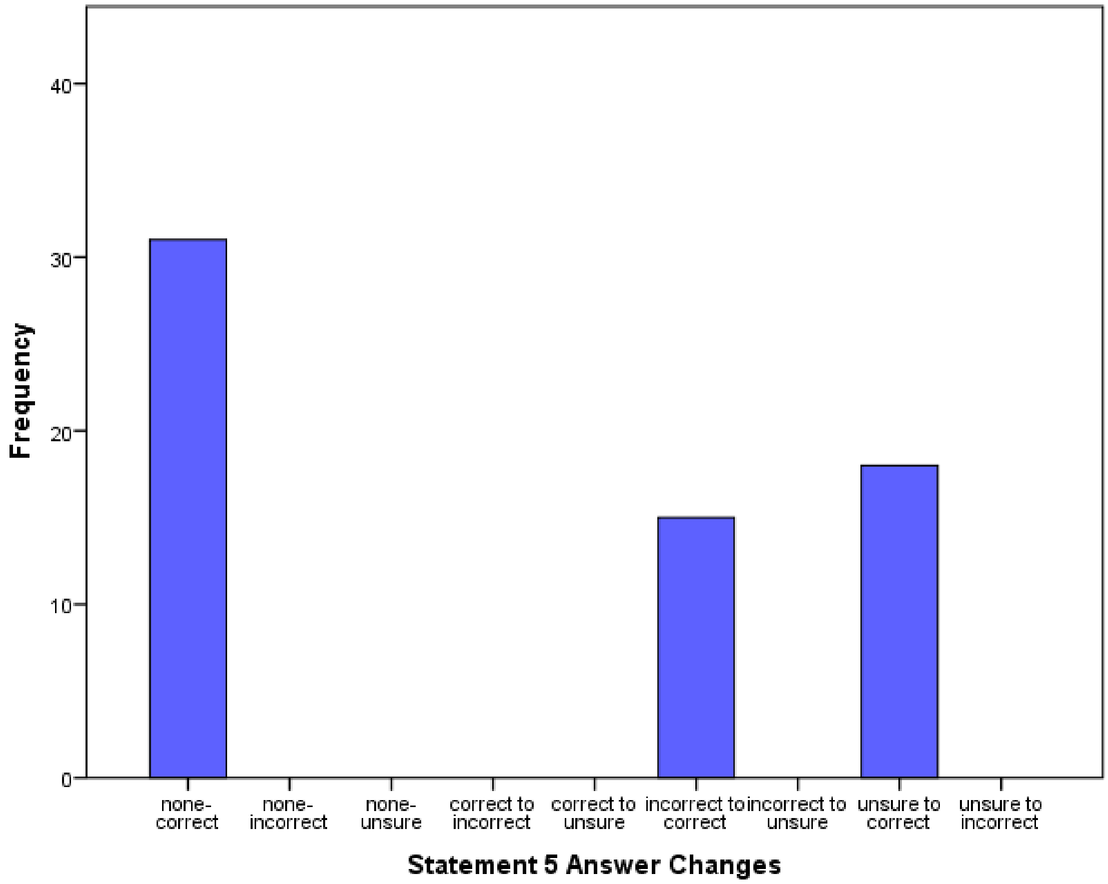


Figure 28: Bar chart depicting answer changes for Statement 5 on the pre- and post-intervention cell knowledge tests

Statement 5 refers to free movement of oxygen across the cell membrane. For this statement, the answer change categories in order of frequency are shown in Table 18.

Table 18: Answer change categories for Statement 5 including frequency and percentage of sample

Category	**Number of students**	**% of sample**
None-correct	31	48%
Unsure to correct	18	28%
Incorrect to correct	15	23%

Most frequently, participants answered correctly both pre- and post-intervention (46%). The second most frequent category was changing from being unsure to answering correctly (28%). The third most frequent was answering incorrectly pre-intervention and changing to the correct answer post-intervention (22%).

4.2.7.5.1 Haptic and non-haptic comparison for Statement 5

The answer changes for Statement 5 were also compared between haptic and non-haptic conditions, which are shown in Figure 29.

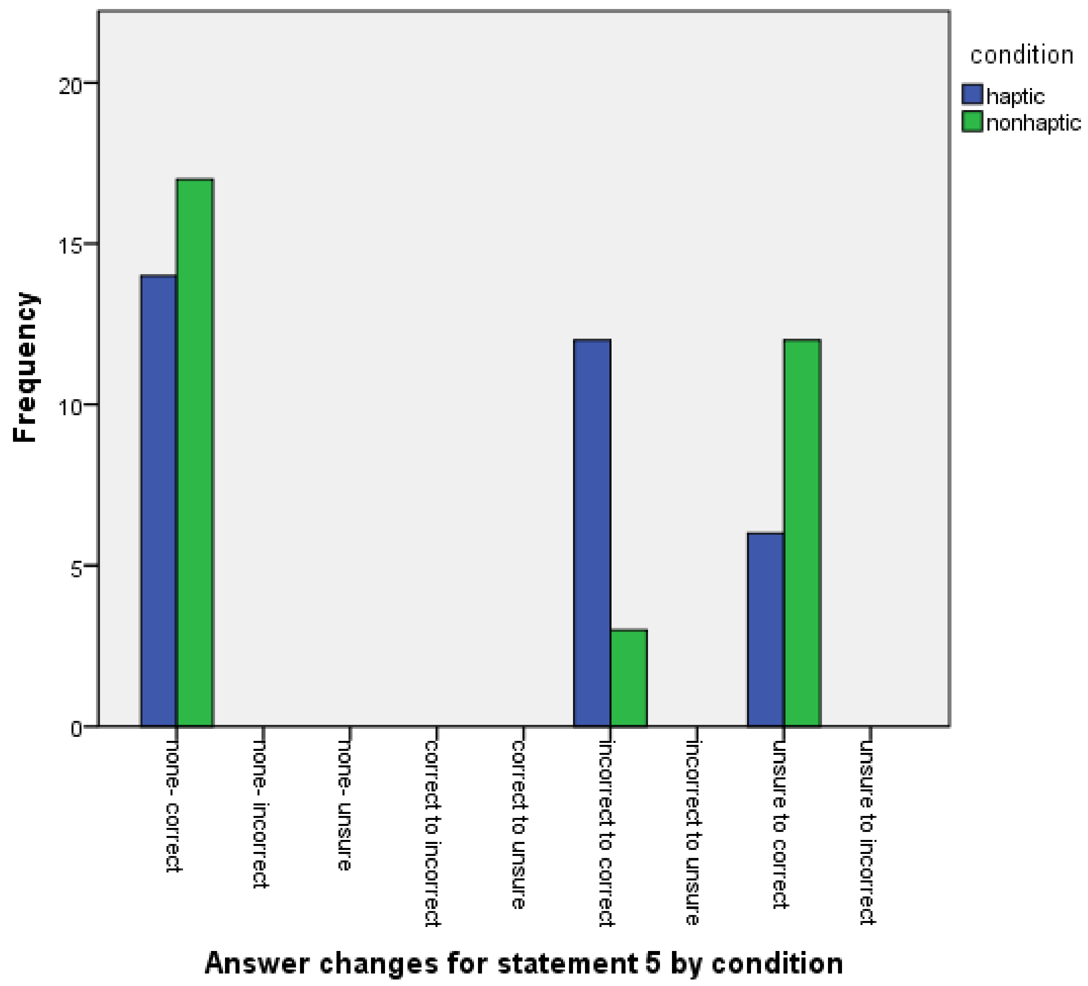


Figure 29: Clustered bar graph of answer changes for Statement 5 separated by condition

Frequencies for each answer change category for Statement 5 separated by haptic and non-haptic conditions can be seen in Table 19.

Table 19: Answer change conditions for Statement 5-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	14	17
Incorrect to correct	12	3
Unsure to correct	6	12

4.2.7.6 Statement 6: Glucose can freely enter and exit a cell (does not need a channel)

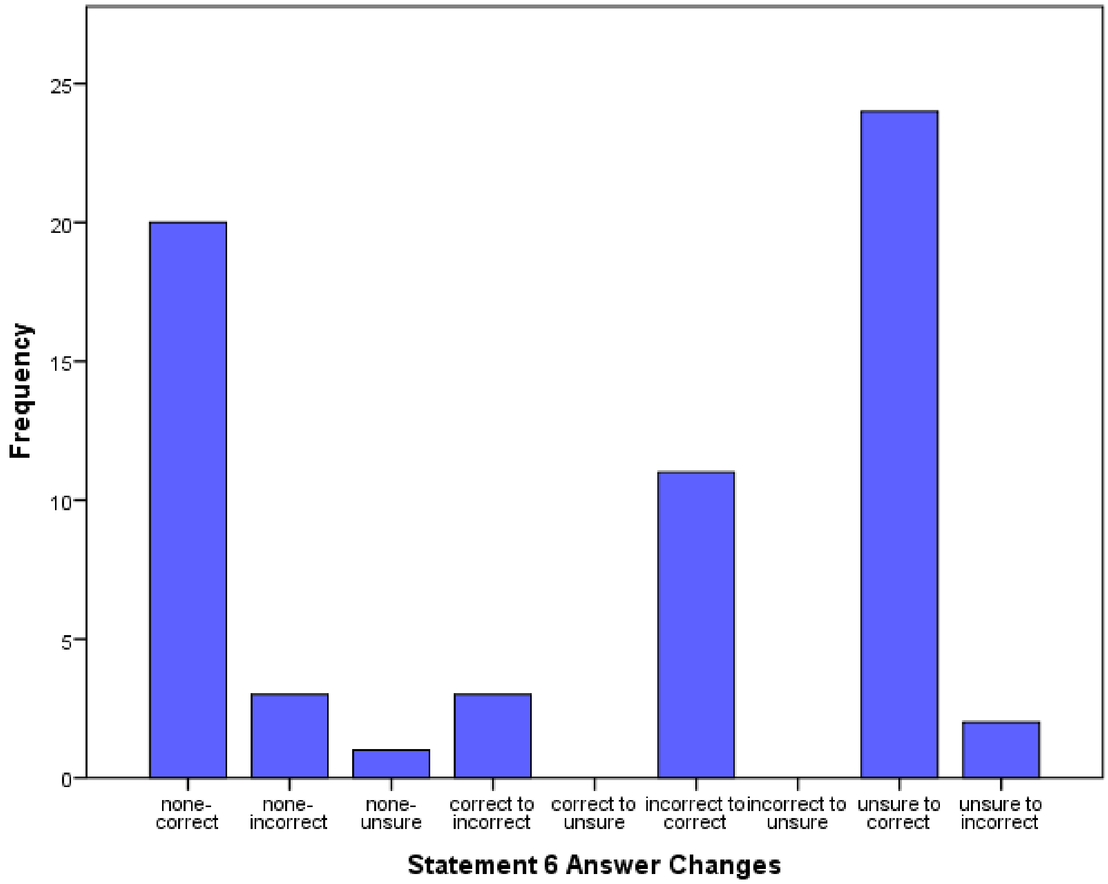


Figure 30: Bar chart depicting answer changes for Statement 6 on the pre- and post-intervention cell knowledge tests.

Statement 6 refers to the movement of glucose across the cell membrane. For this statement, the answer change categories in order of frequency are shown in Table 20.

Table 20: Answer change categories for Statement 6 including frequency and percentage of sample

Category	**Number of students**	**% of sample**
Unsure to correct	24	38%
None-correct	20	31%
Incorrect to correct	11	17%
None-incorrect	3	5%
Correct to incorrect	3	5%
Unsure to incorrect	2	3%
None-unsure	1	2%

For Statement 6, the category with the highest frequency was changing from ‘unsure’ pre-intervention to answering correctly post-intervention (37%). This was followed by answering correctly both the pre- and post-intervention (31%).

4.2.7.6.1 Haptic and non-haptic comparison for Statement 6

The answer changes for Statement 6 were also compared between haptic and non-haptic conditions, which are shown in Figure 31.

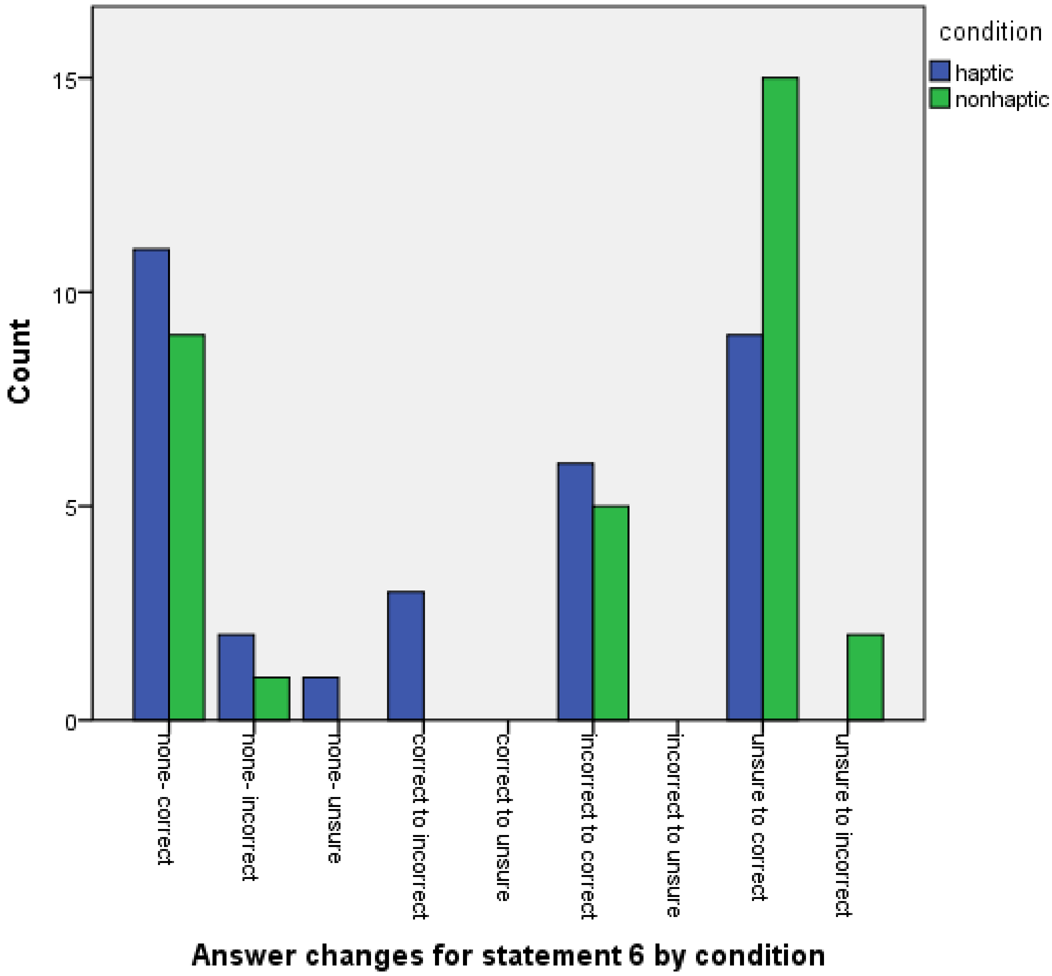


Figure 31: Clustered bar graph of answer changes for Statement 6 separated by condition

Frequencies for each answer change category for Statement 6 separated by haptic and non-haptic conditions can be seen in Table 21.

Table 21: Answer change conditions for Statement 6-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	11	9
None-incorrect	2	1
None-unsure	1	0
Incorrect to correct	6	5
Correct to incorrect	3	0
Unsure to correct	9	15
Unsure to incorrect	0	2

4.2.7.7 Statement 7: Carbon dioxide can freely enter and exit a cell (does not need a channel)

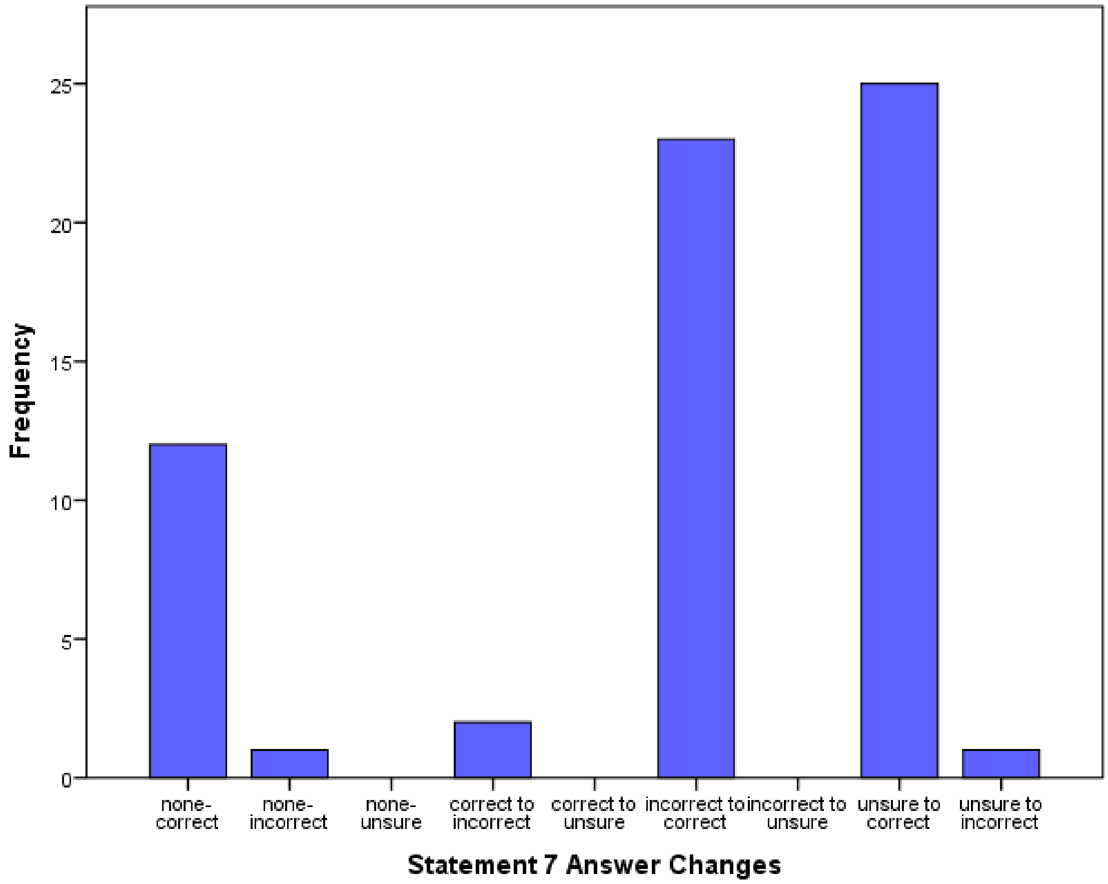


Figure 32: Bar chart depicting answer changes for Statement 7 on the pre and post cell knowledge tests

Statement 7 refers to the topic of the movement of carbon dioxide across the cell membrane. For this statement, the answer change categories in order of frequency are shown in Table 22.

Table 22: Answer change categories for Statement 7 including frequency and percentage of sample

Category	**Number of students**	**% of sample**
Unsure to correct	25	40%
Incorrect to correct	23	36%
None-correct	12	19%
Correct to incorrect	2	3%
None-incorrect	1	2%
Unsure to incorrect	1	2%

For Statement 7, the most frequent answer change was from being unsure pre-intervention to answering correctly post-intervention (40%). This was followed by answering incorrectly pre-intervention to answering correctly post-intervention (36%).

4.2.7.7.1 Haptic and non-haptic comparison for Statement 7

The answer changes for Statement 7 were also compared between haptic and non-haptic conditions, which are shown in Figure 33.

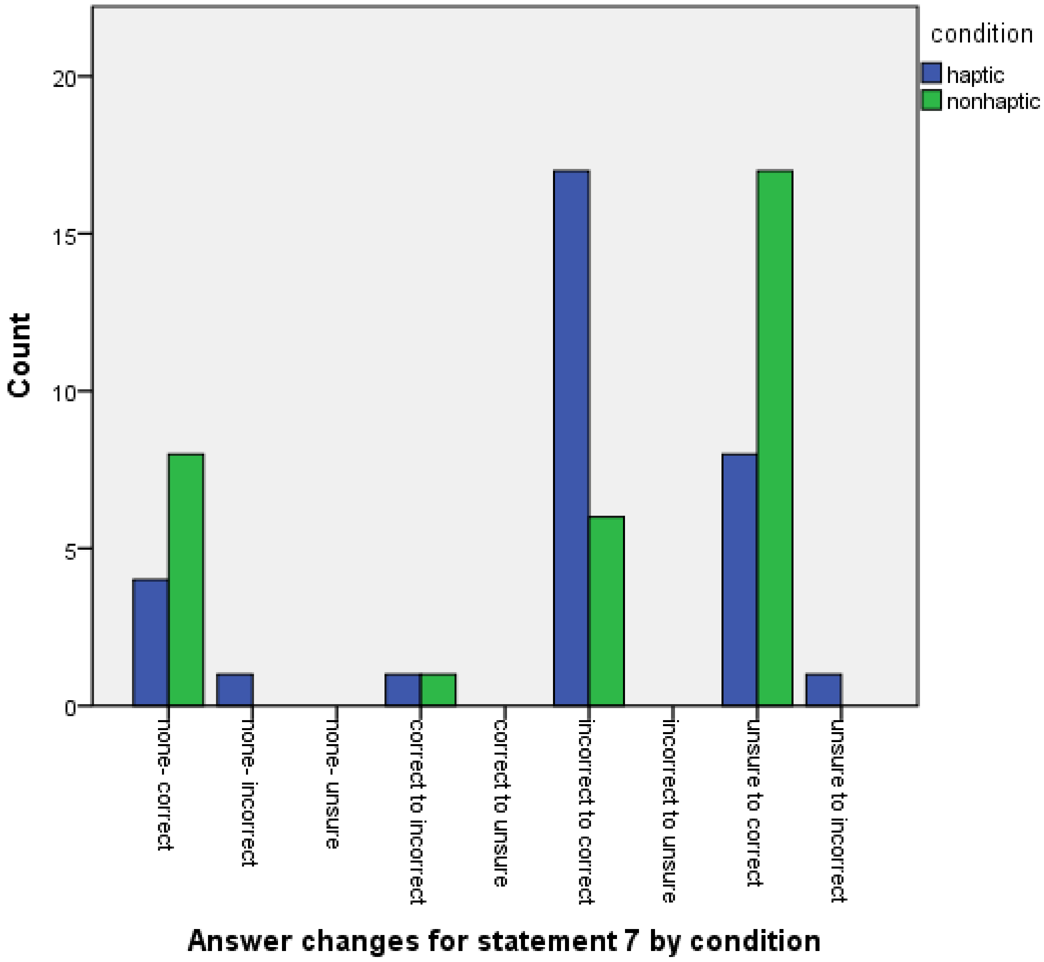


Figure 33: Clustered bar graph of answer changes for Statement 7 separated by condition

Frequencies for each answer change category for Statement 7 separated by haptic and non-haptic conditions can be seen in Table 23.

Table 23: Answer change conditions for Statement 7-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	4	8
None-incorrect	1	0
Correct to incorrect	1	1
Incorrect to correct	17	6
Unsure to correct	8	17
Unsure to incorrect	1	0

4.2.7.8 Statement 8: Sodium can freely enter and exit a cell (does not need a channel)

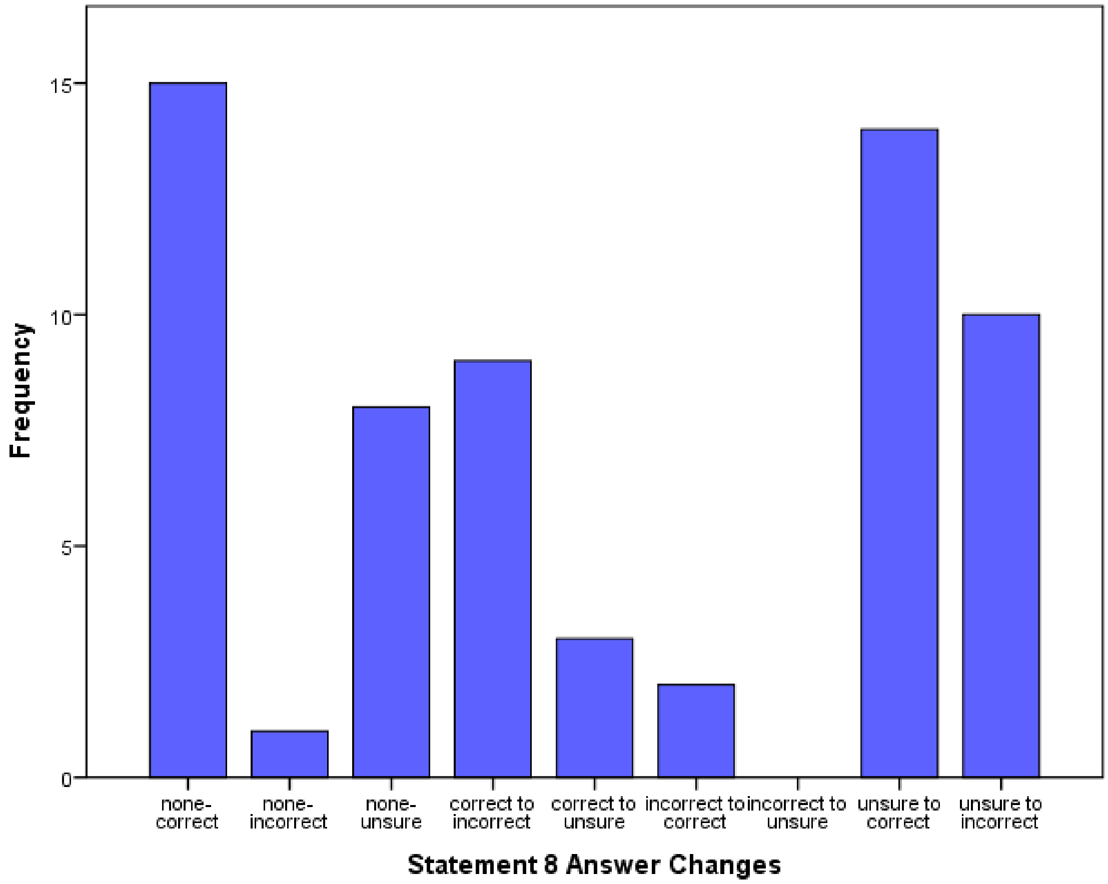


Figure 34: Bar chart depicting answer changes for Statement 8 on the pre- and post-intervention cell knowledge tests

Statement 8 referred to the topic of the movement of sodium across the cell membrane. For this statement, the answer change categories in order of frequency are shown in Table 24.

Table 24: Answer change categories for Statement 8 including frequency and percentage of sample

Category	Number of students	% of sample
None-correct	15	23%
Unsure to correct	14	22%
Unsure to incorrect	10	16%
Correct to incorrect	9	14%
None-unsure	8	13%
Correct to unsure	3	5%
Incorrect to correct	2	3%
None-incorrect	1	2%

For Statement 8, the most frequent category was no change, answering correctly both pre- and post-intervention (23%), followed by unsure to correct (22%). Following closely however, were being unsure pre-intervention to answering incorrectly post-intervention (16%), answering correctly pre-intervention to incorrectly post-intervention (13%) and answering as unsure for both pre- and post-intervention (13%).

4.2.7.8.1 Haptic and non-haptic comparison for Statement 8

The answer changes for Statement 8 were also compared between haptic and non-haptic conditions, which are shown in Figure 35.

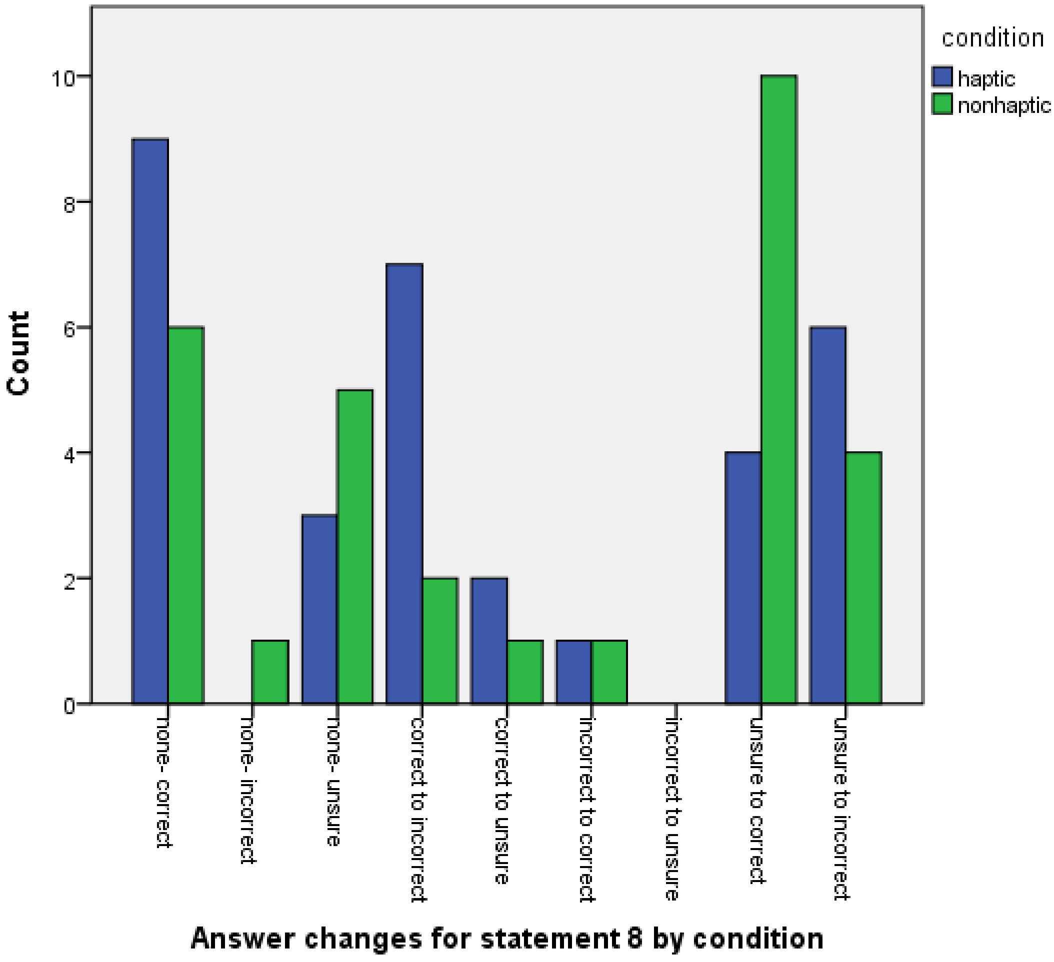


Figure 35: Clustered bar graph of answer changes for Statement 8 separated by condition

Frequencies for each answer change category for statement separated by haptic and non-haptic conditions can be seen in Table 25.

Table 25: Answer change conditions for Statement 8-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	9	2
None-incorrect	1	0
None-unsure	3	5
Correct to incorrect	7	2
Correct to unsure	2	1
Incorrect to correct	1	1
Unsure to correct	4	10
Unsure to incorrect	6	4

4.2.7.9 Statement 9: An oxygen molecule is smaller than a glucose molecule

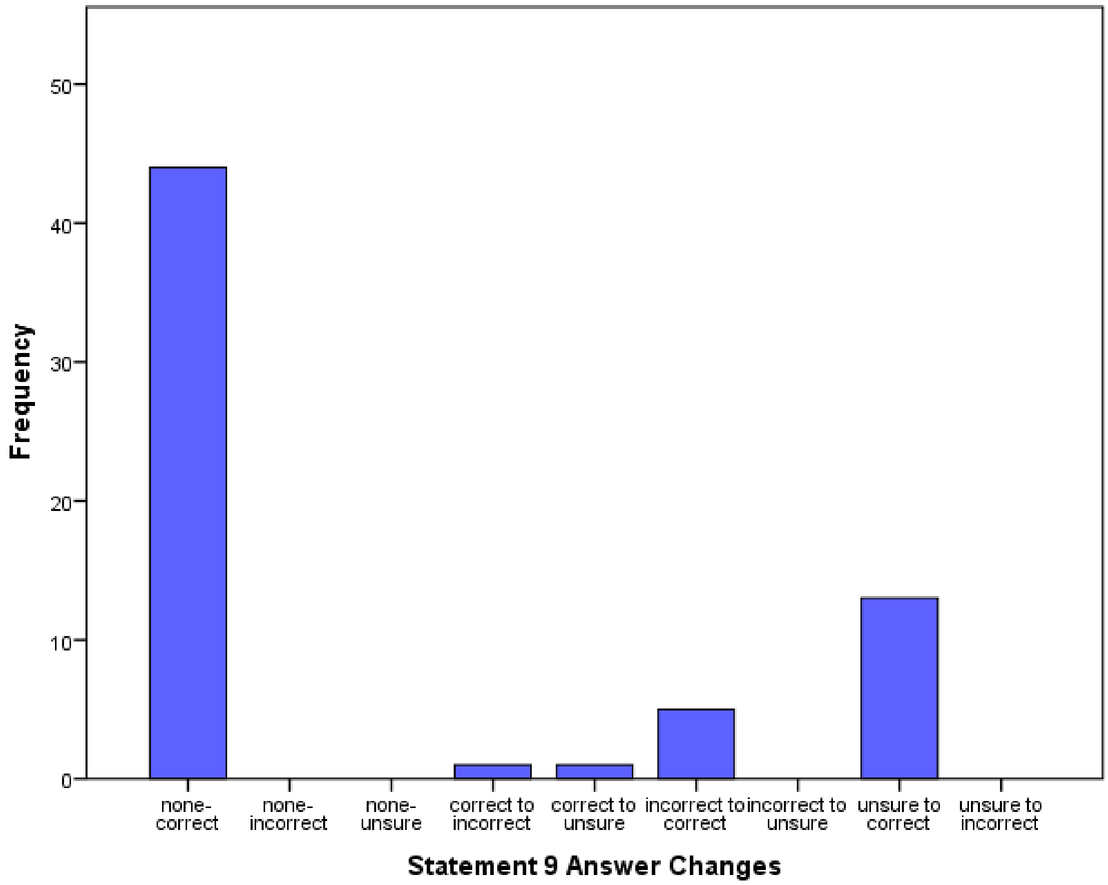


Figure 36: Bar chart depicting answer changes for Statement 9 on the pre- and post-intervention cell knowledge tests

Statement 9 referred to the topic of size and scale of molecules. For this statement, the answer change categories in order of frequency are shown in Table 26.

Table 26: Answer change categories for Statement 9 including frequency and percentage of sample

Category	Number of students	% of sample
None-correct	44	69%
Unsure to correct	13	20%
Incorrect to correct	5	8%
Correct to incorrect	1	2%
Correct to unsure	1	2%

For Statement 9, most participants answered correctly both pre- and post-intervention (69%). Following this, the next most frequent category was changing from unsure to a correct answer (20%).

4.2.7.9.1 Haptic and non-haptic comparison for Statement 9

The answer changes for Statement 9 were also compared between haptic and non-haptic conditions, which are shown in Figure 37.

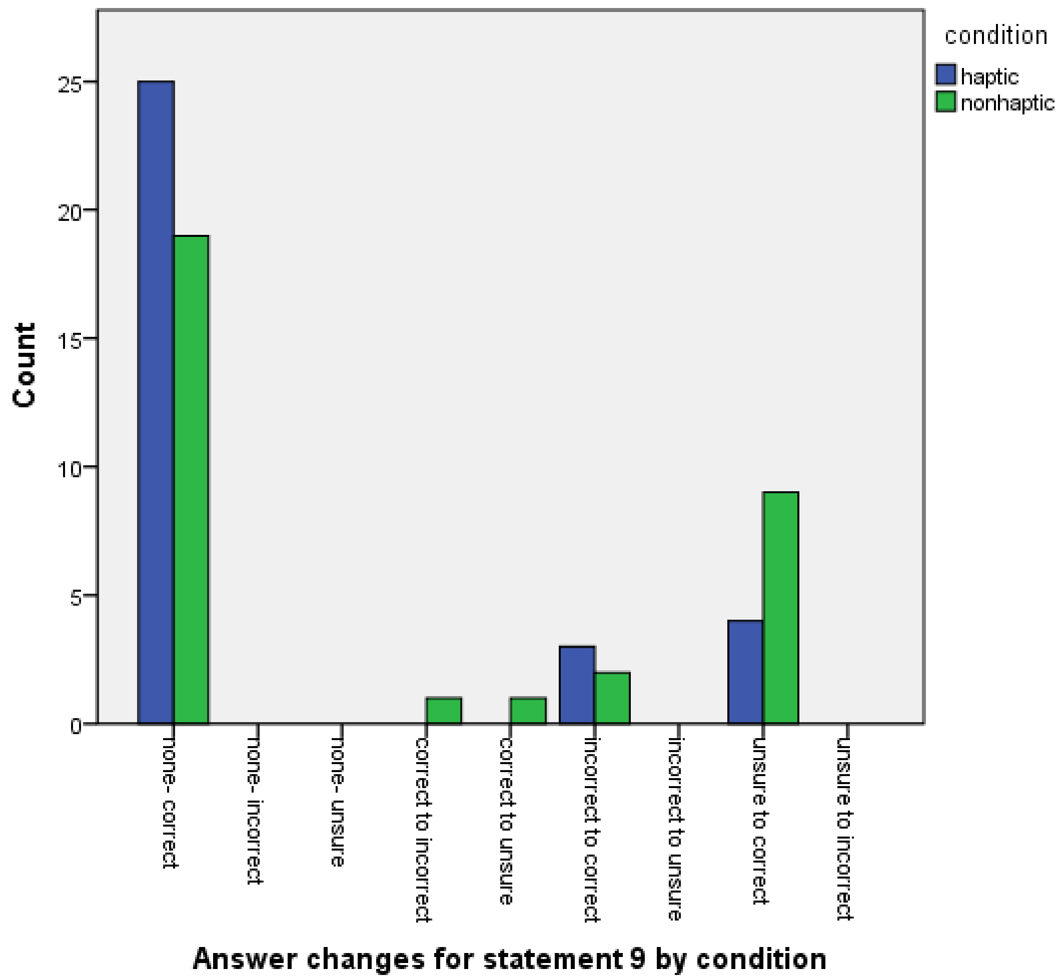


Figure 37: Clustered bar graph of answer changes for Statement 9 separated by condition

Frequencies for each answer change category for Statement 9 separated by haptic and non-haptic conditions can be seen in Table 27.

Table 27: Answer change conditions for Statement 9-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	25	19
Correct to incorrect	0	1
Correct to unsure	0	1
Incorrect to correct	3	2
Unsure to correct	4	9

4.2.7.10 Statement 10: The cell membrane contains about 5 glucose channels

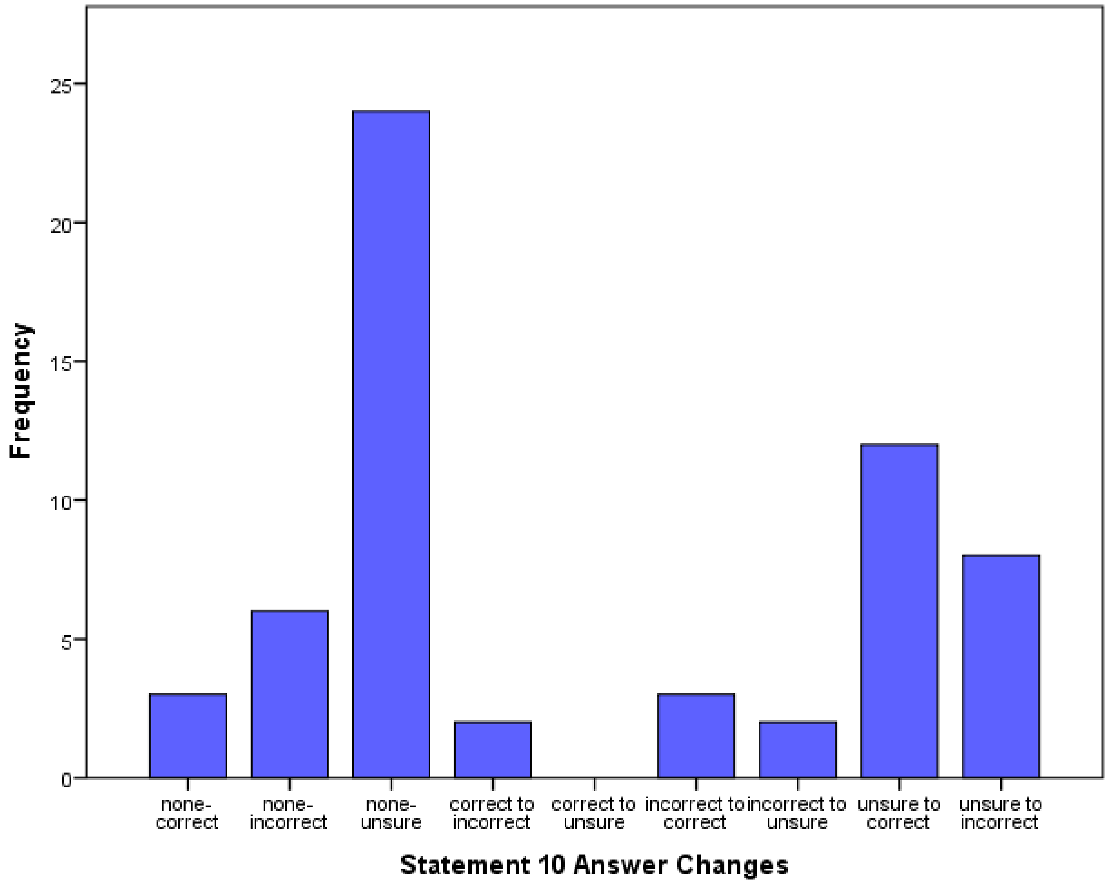


Figure 38: Bar chart depicting answer changes for Statement 10 on the pre- and post-intervention cell knowledge tests

Statement 10 refers to the topic of glucose channels. For this statement, the answer change categories in order of frequency are shown in Table 28.

Table 28: Answer change categories for Statement 10 including frequency and percentage of sample

Category	Number of students	% of sample
None-unsure	24	38
Unsure to correct	12	19%
Unsure to incorrect	8	13%
None-incorrect	6	9%
None-correct	3	5%
Incorrect to correct	3	5%
Correct to incorrect	2	3%
Incorrect to unsure	2	3%

For Statement 10, the most frequent response was unsure both pre- and post-intervention (38%). Of the remaining participants, there was little difference between those who were unsure pre-intervention and changed to a correct answer post-intervention (19%) and those who were unsure pre-intervention and answered incorrectly post-intervention (13%).

4.2.7.10.1 Haptic and non-haptic comparison for Statement 10

The answer changes for Statement 10 were also compared between haptic and non-haptic conditions, which are shown in Figure 39.

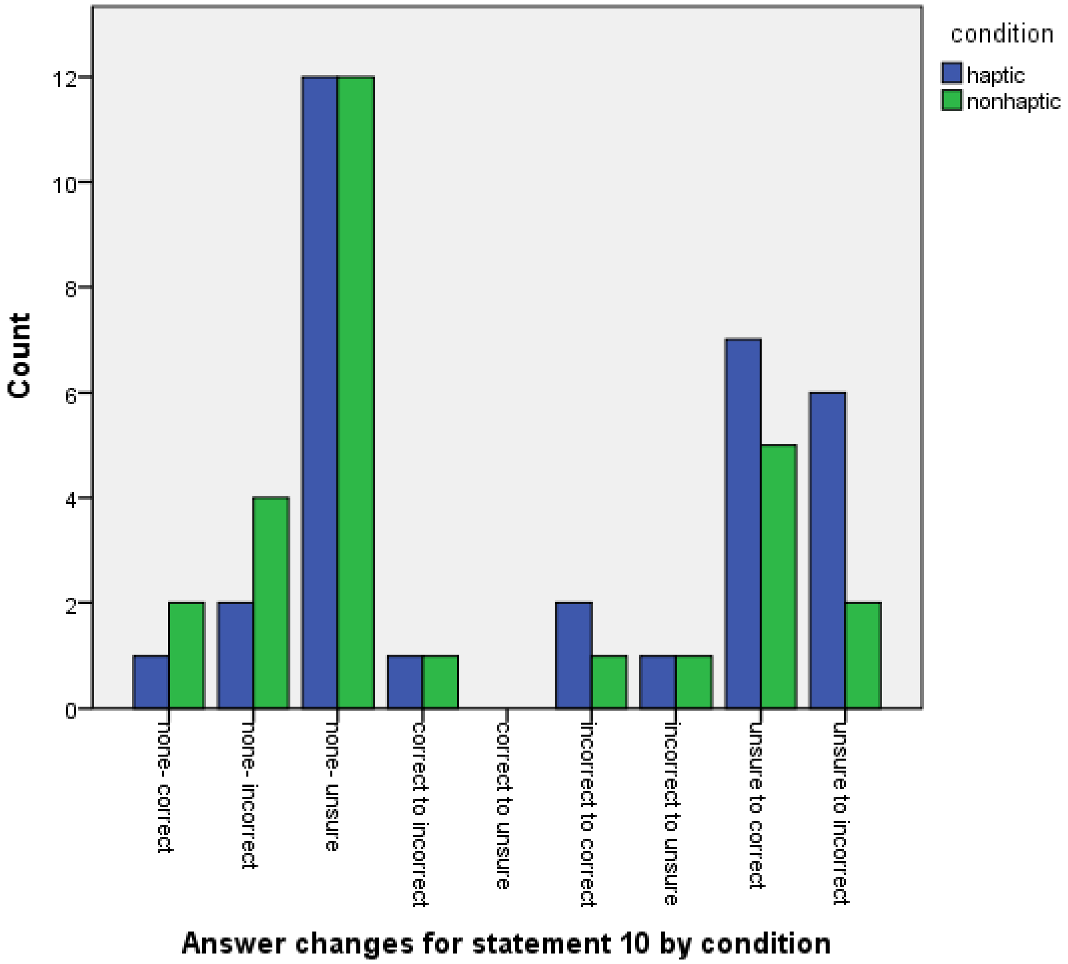


Figure 39: Clustered bar graph of answer changes for Statement 10 separated by condition

Frequencies for each answer change category for Statement 10 separated by haptic and non-haptic conditions can be seen in Table 29.

Table 29: Answer change conditions for Statement 10-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	1	2
None-incorrect	2	4
None-unsure	12	12
Correct to incorrect	1	1
Incorrect to correct	2	1
Unsure to correct	7	5
Unsure to incorrect	6	2

4.2.7.11 Statement 11: If there is an equal amount of oxygen inside and outside the cell it will be harder for oxygen to enter than if there is more oxygen outside

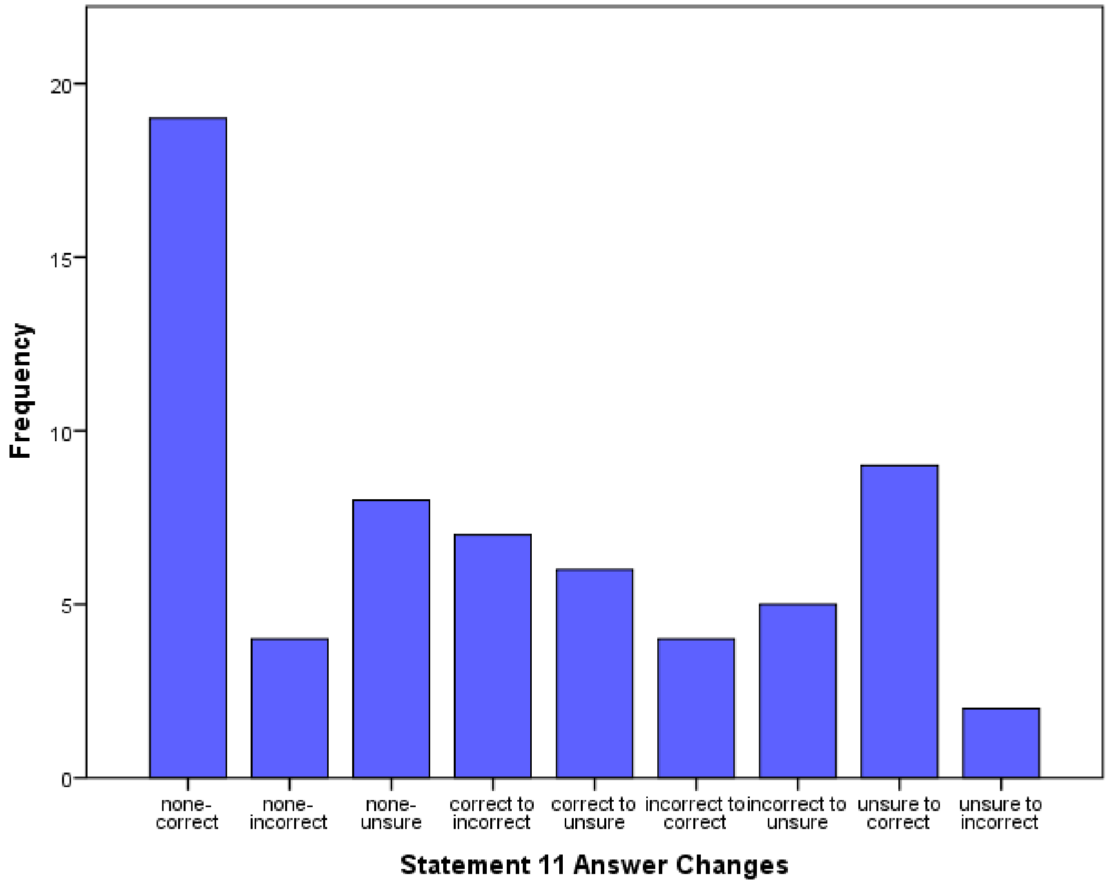


Figure 40: Bar chart depicting answer changes for Statement 11 on the pre- and post-intervention cell knowledge tests

Statement 11 refers to the topic of the diffusion of oxygen across the cell membrane and concentration gradients. For this statement, the answer change categories in order of frequency are shown in Table 30.

Table 30: Answer change categories for Statement 11 including frequency and percentage of sample

Category	Number of students	% of sample
None-correct	19	30%
Unsure to correct	9	14%
None-unsure	8	13%
Correct to incorrect	7	11%
Correct to unsure	6	9%
Incorrect to unsure	5	8%
None-incorrect	4	6%
Incorrect to correct	4	6%
Unsure to incorrect	2	3%

For Statement 11, the most frequent answer category was answering correctly both pre- and post-intervention (30%). This was followed by being unsure pre-intervention to correct post-intervention (14%). There was little difference in the remaining categories for this statement.

4.2.7.11.1 Haptic and non-haptic comparison for Statement 11

The answer changes were also compared between haptic and non-haptic conditions, which are shown in Figure 41.

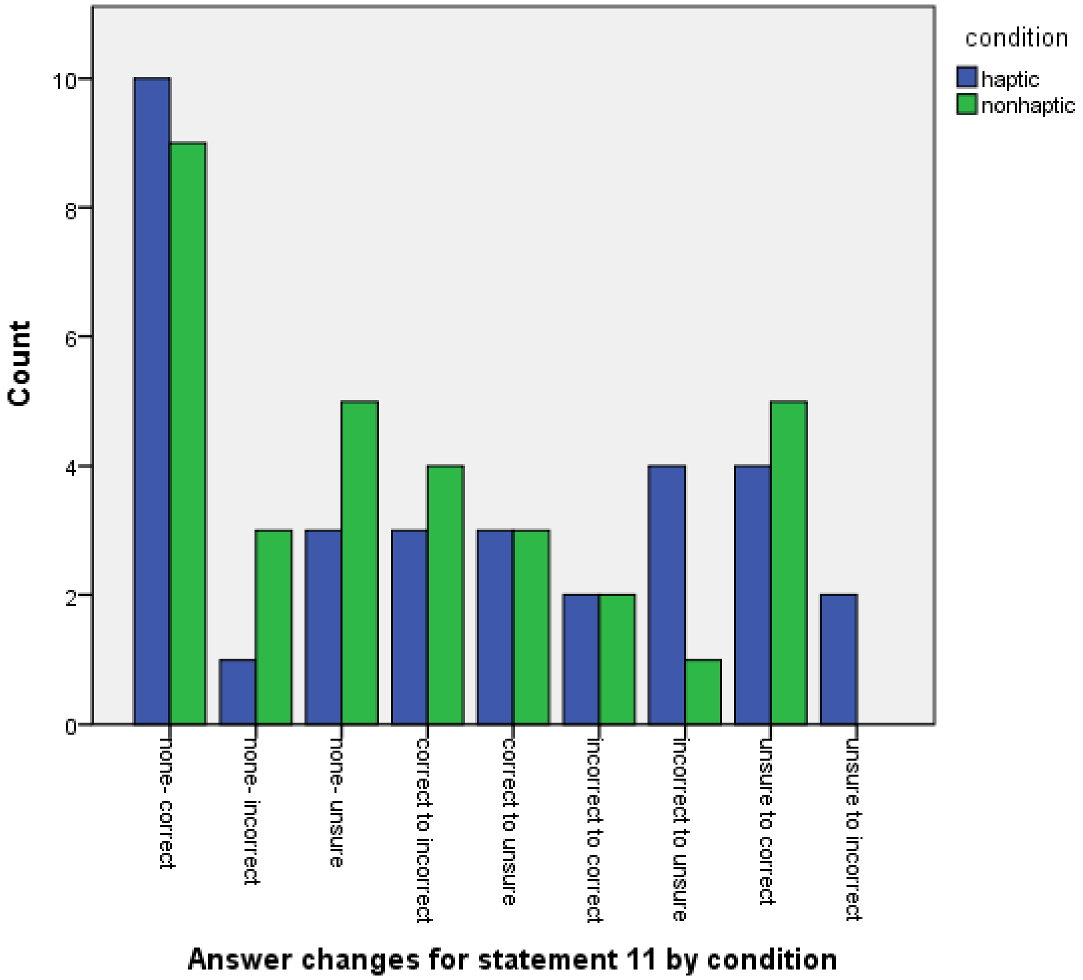


Figure 41: Clustered bar graph of answer changes for Statement 11 separated by condition

Frequencies for each answer change category for statement separated by haptic and non-haptic conditions can be seen in Table 31.

Table 31: Answer change conditions for Statement 11-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	10	9
None-incorrect	1	3
None-unsure	3	5
Correct to incorrect	3	4
Correct to unsure	3	3
Incorrect to correct	2	2
Incorrect to unsure	4	1
Unsure to correct	4	5
Unsure to incorrect	2	0

4.2.7.12 Statement 12: If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside

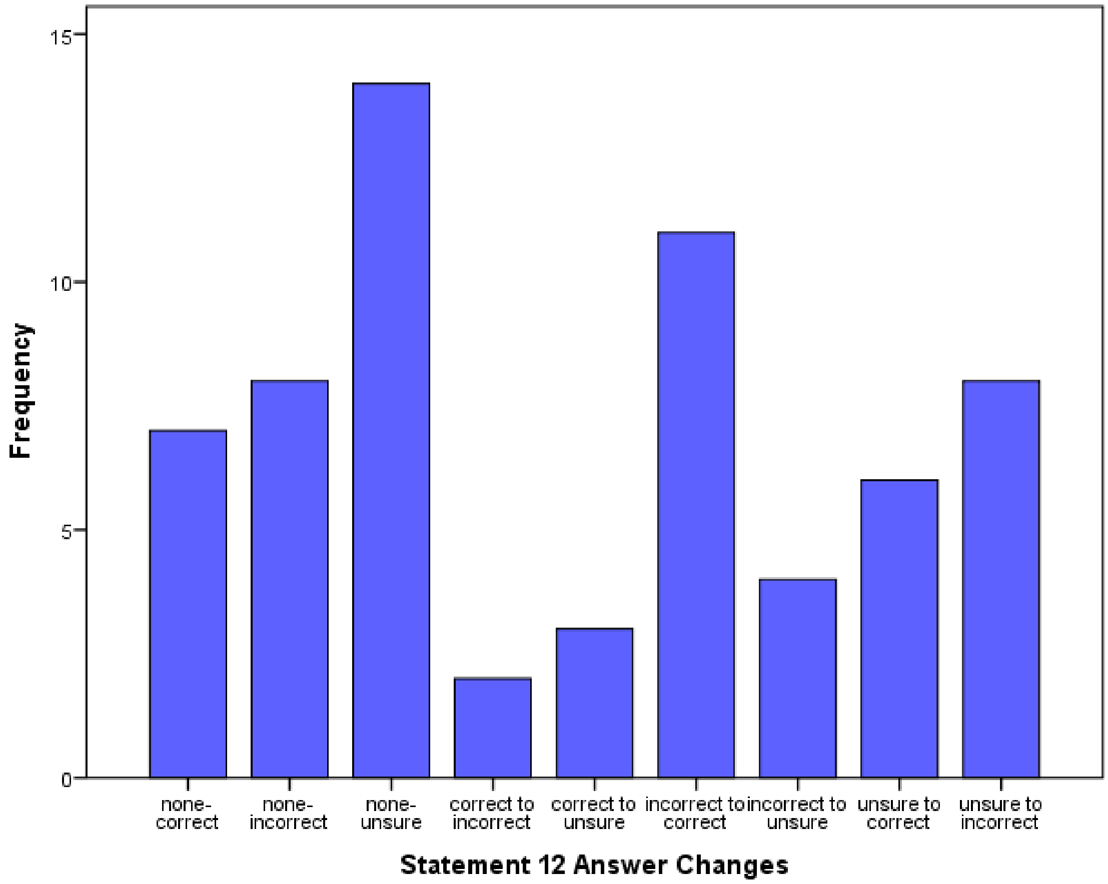


Figure 42: Bar chart depicting answer changes for Statement 12 on the pre- and post-intervention cell knowledge tests

Statement 12 refers to the topic of the diffusion of carbon dioxide across the cell membrane and concentration gradients. This statement refers to the fluidity of the membrane. For this statement, the answer change categories in order of frequency are shown in Table 32.

Table 32: Answer change categories for Statement 12 including frequency and percentage of sample

Category	Number of students	% of sample
None-unsure	14	22%
Incorrect to correct	11	17%
None-incorrect	8	13%
Unsure to incorrect	8	13%
None-correct	7	11%
Unsure to correct	6	9%
Incorrect to unsure	4	6%
Correct to unsure	3	5%
Correct to incorrect	2	3%

The most frequent answer change category for Statement 12 was answering unsure both pre- and post-intervention (22%). Following this was changing from incorrect pre-intervention to a correct answer post-intervention (17%).

4.2.7.12.1 Haptic and non-haptic comparison for Statement 12

The answer changes for Statement 12 were also compared between haptic and non-haptic conditions, which are shown in Figure 43.

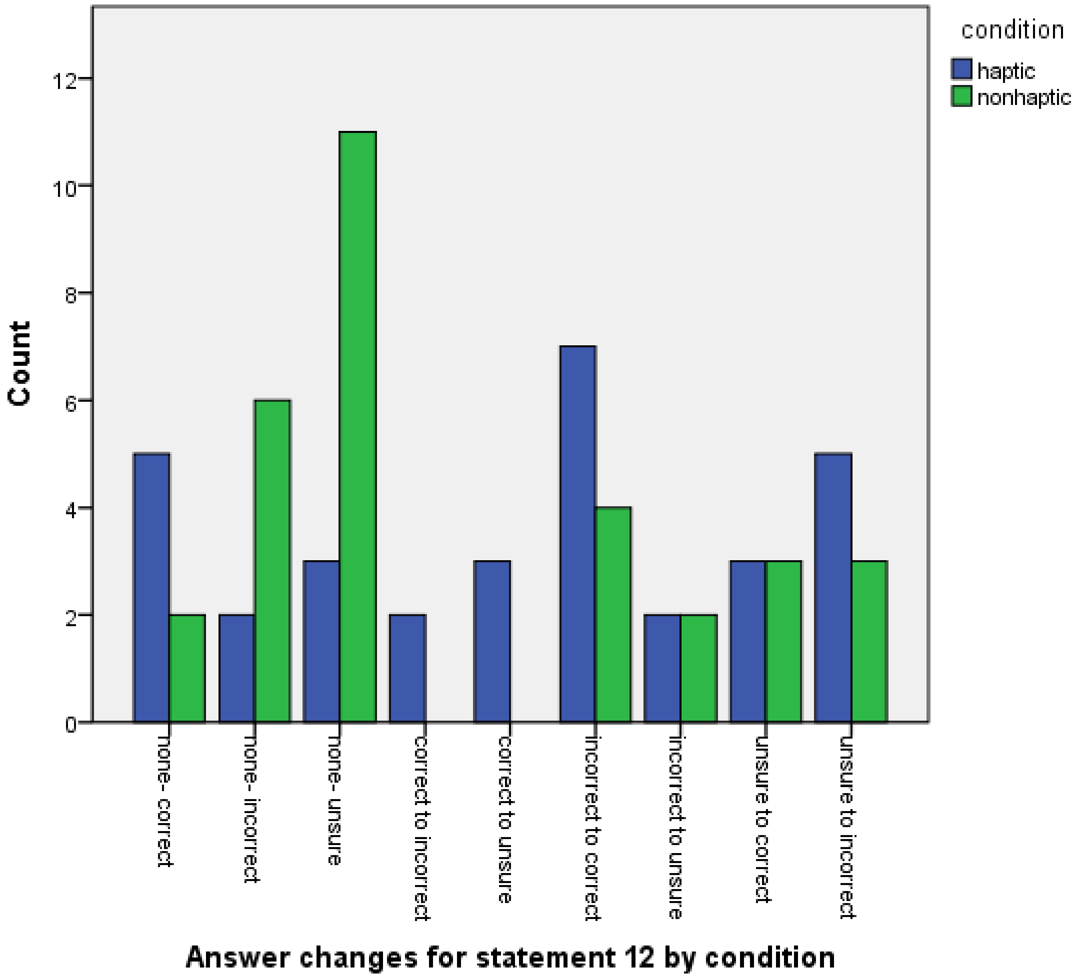


Figure 43: Clustered bar graph of answer changes for Statement 12 separated by condition

Frequencies for each answer change category for Statement 12 separated by haptic and non-haptic conditions can be seen in Table 33.

Table 33: Answer change conditions for Statement 12-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	9	2
None-incorrect	1	0
None-unsure	3	5
Correct to incorrect	7	2
Correct to unsure	2	1
Incorrect to correct	1	1
Unsure to correct	4	10
Unsure to incorrect	6	4

4.2.7.13 Statement 13: During aerobic respiration a cell uses oxygen and glucose

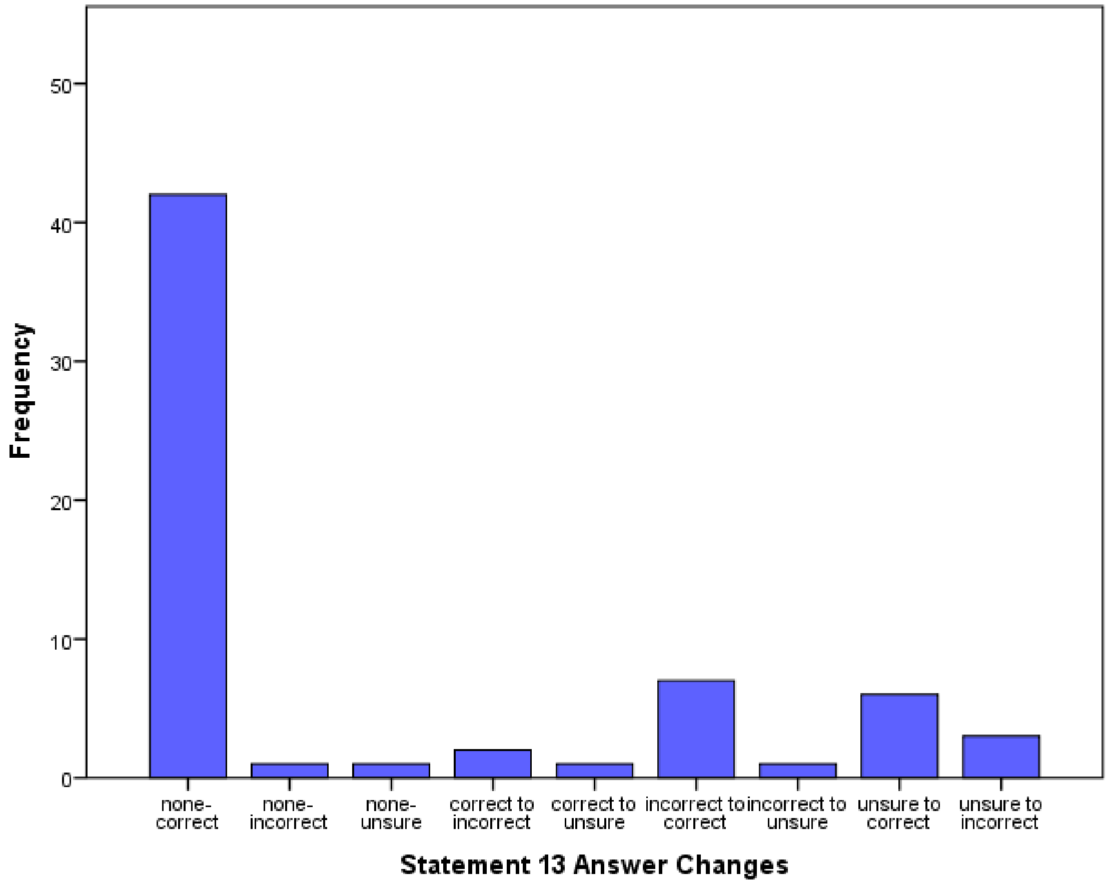


Figure 44: Bar chart depicting answer changes for Statement 13 on the pre and post-intervention cell knowledge tests.

Statement 13 refers to the topic of aerobic respiration. For this statement, the answer change categories in order of frequency are shown in Table 34.

Table 34: Answer change categories for Statement 13 including frequency and percentage of sample

Category	Number of students	% of sample
None-correct	42	66%
Incorrect to correct	7	11%
Unsure to correct	6	9%
Unsure to incorrect	3	5%
Correct to incorrect	2	3%
None-incorrect	1	2%
None-unsure	1	2%
Incorrect to unsure	1	2%

For Statement 13, most participants answered correctly both pre- and post-intervention (66%). Following this were changing from incorrect to correct (11%) and unsure to correct (9%). Therefore, most students answered correctly post-intervention for Statement 13.

4.2.7.13.1 Haptic and non-haptic comparison for Statement 13

The answer changes were also compared between haptic and non-haptic conditions, which are shown in Figure 45.

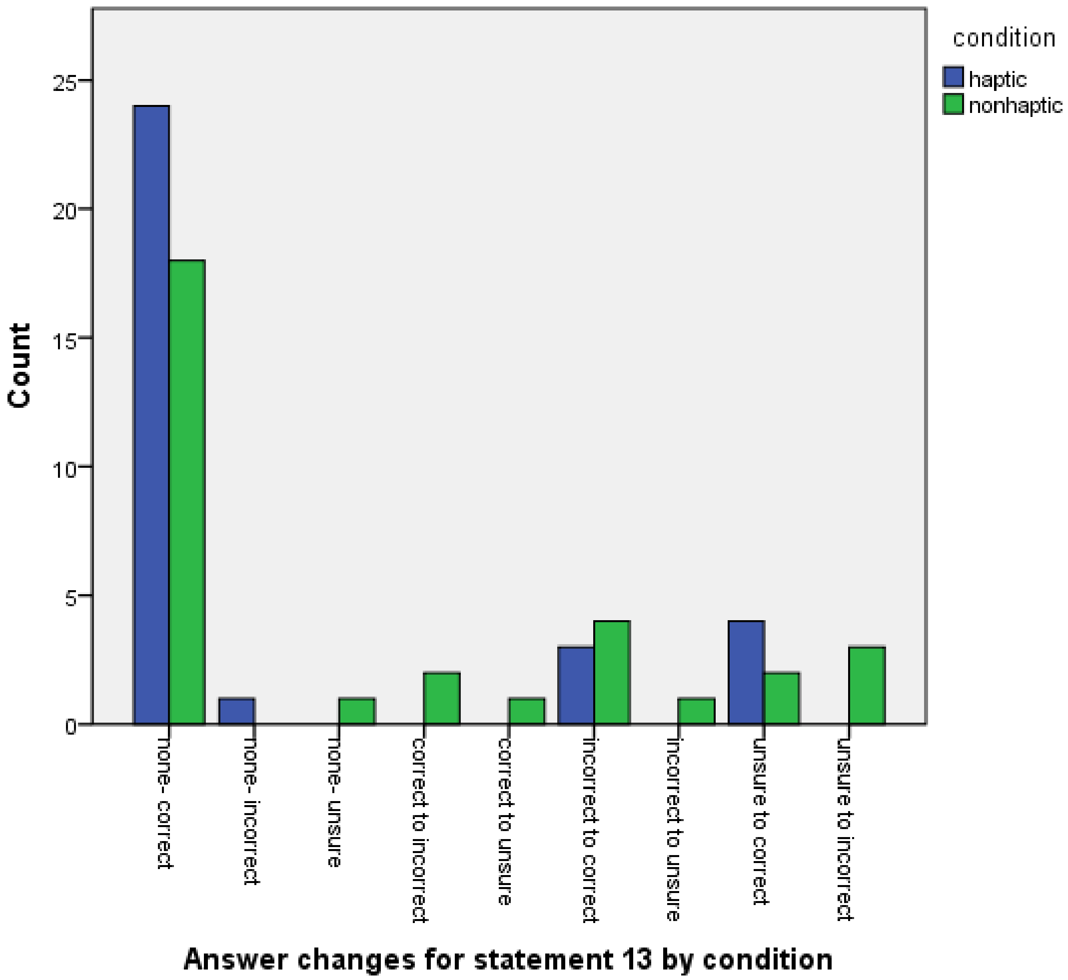


Figure 45: Clustered bar graph of answer changes for Statement 13 separated by condition

Frequencies for each answer change category for Statement 13 separated by haptic and non-haptic conditions can be seen in Table 35.

Table 35: Answer change conditions for Statement 13-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	24	18
None-incorrect	1	0
None-unsure	0	1
Correct to incorrect	0	2
Correct to unsure	0	1
Incorrect to correct	3	4
Incorrect to unsure	0	1
Unsure to correct	4	2
Unsure to incorrect	0	3

4.2.7.14 Statement 14: During aerobic respiration a cell produces oxygen and water

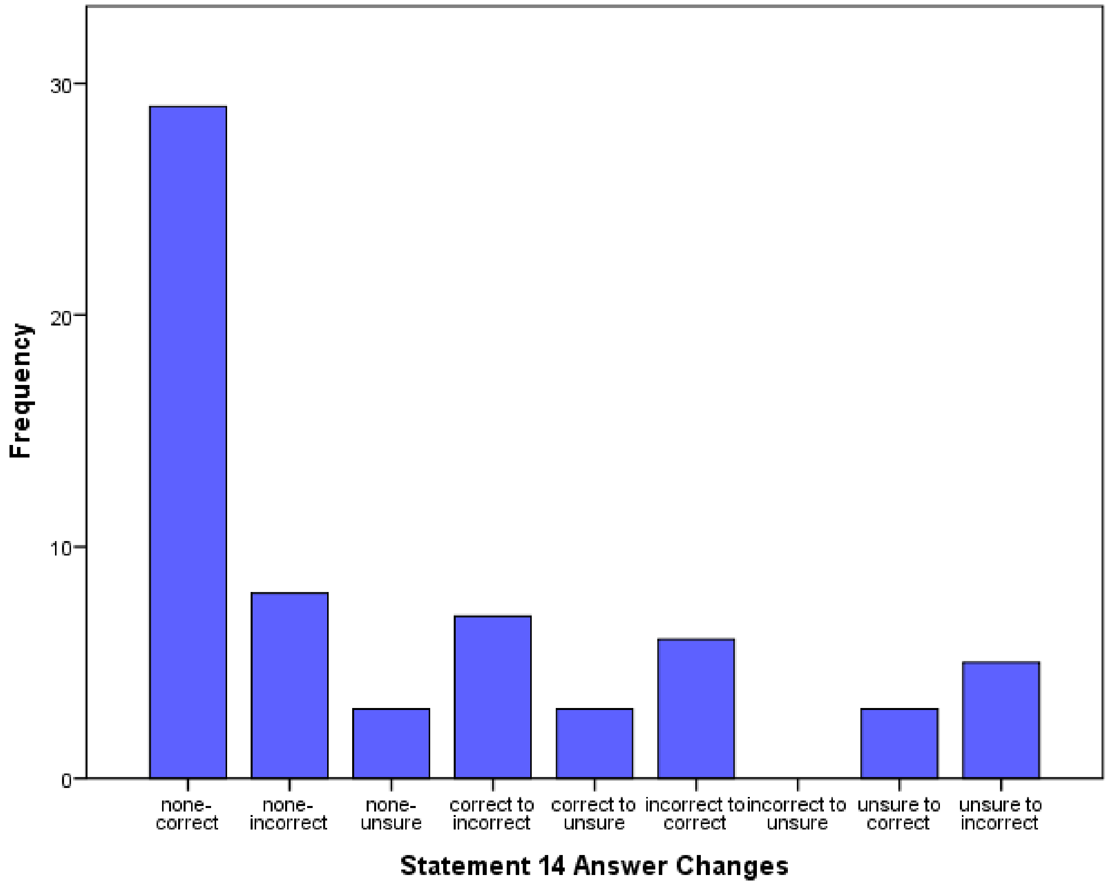


Figure 46: Bar chart depicting answer changes for Statement 14 on the pre- and post-intervention cell knowledge tests

Statement 14 refers to the topic of aerobic respiration. For this statement, the answer change categories in order of frequency are shown in Table 36.

Table 36: Answer change categories for Statement 14 including frequency and percentage of sample

Category	Number of students	% of sample
None-correct	29	45%
None-incorrect	8	13%
Correct to incorrect	7	11%
Incorrect to correct	6	9%
Unsure to incorrect	5	8%
None-unsure	3	5%
Correct to unsure	3	5%
Unsure to correct	3	5%

The most frequent category for Statement 14 was answering correctly both pre- and post-intervention (45%). The remainder of the categories have few variances in their frequencies.

4.2.7.14.1 Haptic and non-haptic comparison for Statement 14

The answer changes were also compared between haptic and non-haptic conditions, which are shown in Figure 47.

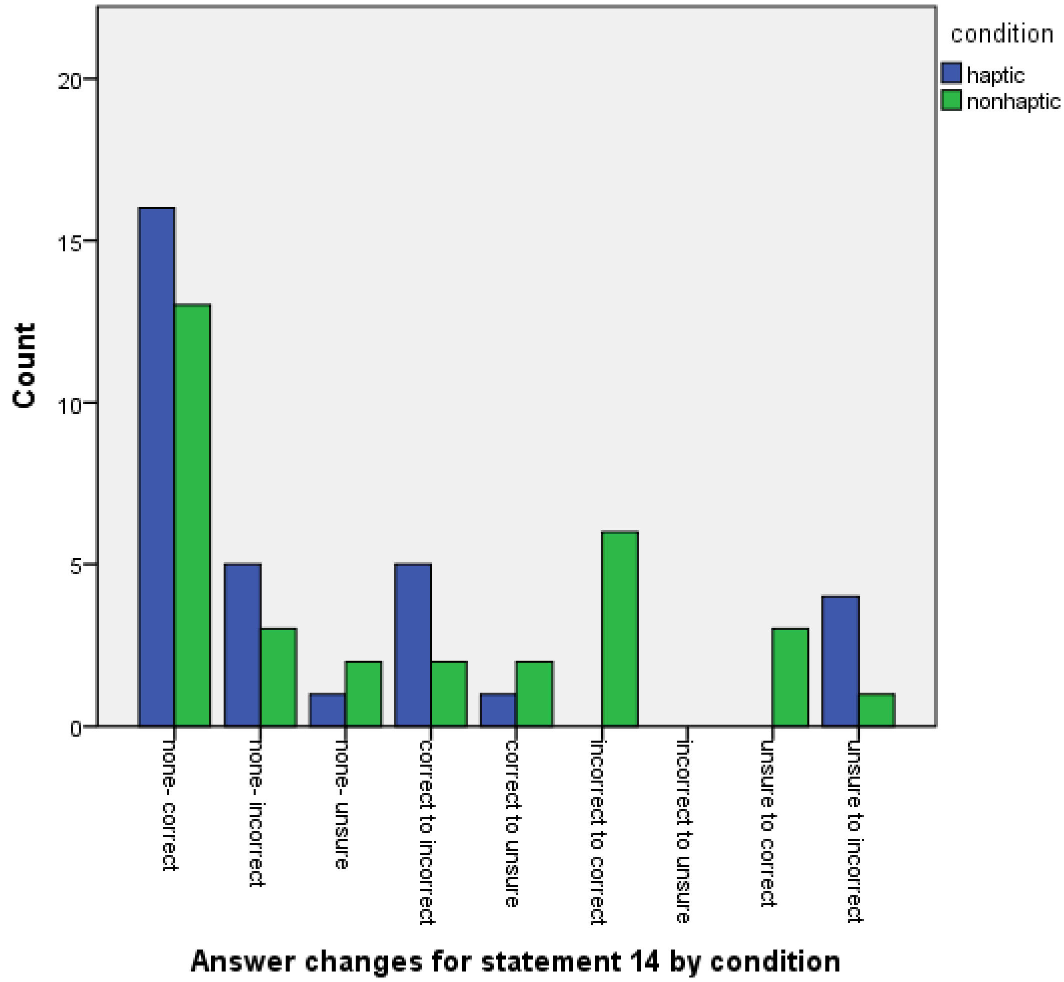


Figure 47: Clustered bar graph of answer changes for Statement 14 separated by condition

Frequencies for each answer change category for Statement 14 separated by haptic and non-haptic conditions can be seen in Table 37.

Table 37: Answer change conditions for Statement 14-frequencies by condition

	No. of students	
Category	**Haptic**	**Non-haptic**
None-correct	16	13
None-incorrect	5	3
None-unsure	1	2
Correct to incorrect	5	2
Correct to unsure	1	2
Incorrect to correct	0	6
Unsure to correct	0	3
Unsure to incorrect	4	1

4.2.8 Analysis of dyad independence

As discussed in Sections 4.2.5 and 4.2.6, ANOVA and ANCOVA were used to determine the statistical significance of the differences in pre, post and retention-test scores, the interaction effects of the condition on the change in those scores over time, and any significant covariate effects. The ANOVA and ANCOVA are considered as robust statistical tests, which are generally tolerant against violations of their assumptions. However, the violation of the assumption of independence-of-observations can lead to a loss of robustness (Kenny & Judd, 1986). The independence-of-observations ANOVA assumption can be violated when individual-level data is collected from more than one person from the same dyad (O'Connor, 2004). A dyad can be described as "the fundamental unit of interpersonal interaction and interpersonal relations" (Kenny et al., 2006, p. 1), and in the context of this study refers to each pair of students in this study, as although students worked collaboratively during the intervention, they were tested individually at pre, post and retention time-points.

To measure the nonindependence between members of dyads in this study, dyadic data analysis techniques will be used to determine the extent to which the outcomes of two members of the same dyad are correlated (Alferes & Kenny, 2009). The dyads in this study were study partners and therefore classified as "indistinguishable", as there was no meaningful factor that can be used to order the two members (Kenny et al., 2006). For indistinguishable dyads, nonindependence can be assessed by the intraclass correlation coefficient (ICC) (Kenny et al., 2006).

To determine any nonindependence between members of dyads for this study, an ICC was conducted via mixed modelling in SPSS, using the change in knowledge score from pre to post-test, post to retention-test and pre to retention-test time-points. The estimated CSR Rho was used for the ICC. This analysis controlled for the effect of condition (haptic or non-haptic) whilst determining any correlation between the change in knowledge across time points within dyads. For this test, a more liberal alpha level of 0.20 was used as recommended by Kenny et al. (2006, p. 50) to avoid erroneously rejecting the existence of nonindependence (Type II error) (Grawitch & Munz, 2004; Kenny et al., 2006).

For the change in score from pre to post-test, there was no significant correlation between dyad members (CSR Rho= .15, p=.42), meaning that the change in knowledge score from pre to post-test was not significantly more similar for members of the same dyad compared to members of separate dyads. However, there was a significant correlation between dyad members in their change in score from pre to retention-test (CSR Rho= .26, p=.17) and from post to retention-test (CSR Rho= .51, p=.002). These ICCs show that there was no significant nonindependence within dyads in student's change in scores from pre-test to post-test, but there was a significant level of nonindependence within dyads in their change from pre-test to retention-test and post-test to retention-test score.

The ICCs show that the independence-of-observations assumption is violated for students in this study for their change in knowledge score from pre to retention and post to retention time points, suggesting that who the students worked with during the intervention had an influence on their retention of knowledge. The limitations regarding nonindependence in this study are discussed further in Section 5.7.

4.2.9 Quantitative analysis summary

In this quantitative results section, the cell knowledge test scores, tests of spatial ability and test of fine dexterity were explored. Paired t-tests showed no significant differences in pre-test scores between the two conditions (haptic and non-haptic) and data was shown to be normally distributed. A mixed ANOVA showed a significant increase in scores from pre-test to post-test, meaning that overall, the sample significantly increased their cell knowledge by using the system. To explore the learning gains in more detail, each statement in the true/false/unsure section of the cell knowledge test was examined and how participants changed their answers from pre-test to post-test was displayed visually. The meaning of these results in the context of this study will be discussed in Section 5.2.2.

This section has used inferential statistical methods to analyse quantitative data from the cell knowledge, spatial ability, and fine dexterity tests. The ANOVA showed a significant main effect of time (knowledge test scores increased across time points), but no interaction effect of condition (condition did not influence change of scores over time). The ANCOVA showed that only the finger fine dexterity score was identified as a significant covariate on the effect of time (finger fine dexterity had a significant effect on the change in scores over time), and the Pearson’s r correlation showed that there was a significant negative correlation between finger fine dexterity scores and change in cell knowledge test scores from post-intervention to retention (fine dexterity was shown to effect the retention of scores in a negative direction).

The results of the thematic analysis of the interview data will be reported in next section (4.3.1), which will be used to explore RQ4, and to gain further insight into the quantitative results found in this section.

4.3 Qualitative analysis

This section will report the results of the thematic analysis conducted on the transcripts of the interviews, the process of which is described in detail in Section 3.4.8.6. The themes that emerged from the data and how this data works together with the quantitative results will be discussed for a more in-depth exploration into the research questions.

4.3.1 Thematic analysis

As discussed in Section 3.4.8.6, to analyse the data gathered from the interviews and identify important patterns emerging in this study the scripts were initially open coded and then analysed thematically. The data was coded following the guidelines provided in Braun and Clarke (2006) (described in more detail in Section 3.4.8.6.1), which identified several themes. Some of the themes identified concern matters beyond the scope of this thesis, such as themes detailing the more technical and developmental aspects of the system (e.g. wishes for improvement) and potentially interesting educational themes not related to the research questions (e.g. learning style beliefs). Table 38 displays all themes that were identified in the thematic analysis, with those themes thought to be relevant to this thesis highlighted in **bold**. Table 38 also shows how many items of data were coded to these themes and separates the number of items by haptic and non-haptic conditions.

Table 38: Themes with the number of items coded included separated by haptic and non-haptic conditions

Theme	**Number of items coded**	**Number of items coded from the haptic condition**	**Number of items coded from the non-haptic condition**
Comparison with regular teaching	170	64	106
- **Preference for interaction/personal experience**	49	24	25
Concerns for mainstream use	36	16	20
- Lack of revision	7	3	4
Difficulties	307	162	145
- Dizziness	10	6	4
- **Thimble issues**	21	14	7
- **Grasping particles**	43	17	26
- **Space restriction**	17	11	6
- **Task difficulty**	30	21	9
- Instructions needed	5	4	1
- **Technical problems**	60	31	29
- Uncomfortable equipment	16	4	12
- Visual confusion	16	12	4
Distraction	26	15	11
Easy	110	49	61

Focus	14	8	6
Haptics	97	63	34
- **Concentration gradient**	10	9	1
- **Not able to feel**	14	2	12
- Vibration	12	11	1
Labels and identification		10	23
Learning	115	59	56
- Application of knowledge	7	1	6
- **Increased understanding**	111	55	56
- Lack of or problems with learning	28	15	13
- **Learn by discovering and interacting**	45	22	23
- **Membrane channels**	40	23	17
- **Molecules type and size**	37	16	21
- Questioning	5	1	4
- **Retention/memory**	43	22	21
- **Subverting expectations**	24	16	8
Learning collaboratively	321	131	190
- **Communication and discussion**	69	31	38
	25	11	17

- **Barriers to communication**	13	6	7
- **Remaining grounded and safe**	104	39	65
- **Roles as pilot and co-pilot**	27	10	17
- **Different views of the system**			
Learning style beliefs	15	8	7
Liked features	161	72	89
- **Feel forces**	16	14	2
- **Feeling in general**	18	9	9
- **Moving things**	37	16	21
- **Seeing**	75	24	51
Misunderstanding	30	11	19
Need for feedback or confirmation	18	8	10
Novelty	16	5	11
Praise for the system	128	53	75
Realistic	10	2	8
Using prior knowledge	6	0	6
Value for difficult subjects	5	0	5
Visualisation	48	19	29

Wishes for improvement	186	100	86
- Additional sensory input	14	6	8
- Extra learning content	24	14	10
- Workspace and restriction of space	13	9	4

Several themes were identified from the data, covering a broad range of topics. The interview questions were chosen to gather data on a range of technical and educational topics relevant for the larger project encompassing this PhD, and therefore not all the information gathered from the interviews was relevant for the research questions in this thesis. From the whole set of themes identified from the data, certain themes were chosen to be discussed in this thesis according to their relevance to the research questions.

Themes identified which were thought to be relevant to this thesis were: praise for the system, liked features, novelty, comparison with regular teaching, value for difficult subjects, learning, difficulties, easy, learning collaboratively, visualisation, realistic, misunderstandings and haptics.

For the sake of clarity, terms were created to describe the different categories of themes presented in this section. As discussed above, the only themes that will be discussed in this section are those identified as relevant to the research questions. These themes will be separated into two categories: major themes and minor themes. Major themes will refer to themes which identify important points or present major implications for the research questions. These will be presented first. Minor themes will refer to themes which may have had a smaller presence in the data but nonetheless constituted patterns deserving of discussion. Sub-themes of minor or major themes will be simply referred to as ‘sub-themes’. A summary of the categories of themes present in this section is shown in Table 39.

Table 39: Categories of themes and their descriptions

Category of Theme	**Description**
Theme	Theme identified from the analysis as relevant for the research questions.
Sub-Theme	A ‘child’ category within a theme. These represent patterns identified from the data within a theme.

Major theme	Theme which was found as a major contribution to the research questions, or present prominent points or implications.
Minor theme	Theme found as a pattern in the data with relevance to the research questions, but with do not present major points or implications as major themes do.

This section will discuss these themes, their presence in haptic and non-haptic interviews and discuss what insights they might provide in relation to RQ4.

4.3.1.1 Major Themes

4.3.1.1.1 Haptics

During this experiment, students were separated into two conditions: haptic and non-haptic. The haptic condition included haptic feedback and the non-haptic condition had all haptic feedback switched off to make a direct comparison on the effect of the haptic feedback on learning.

Naturally, during the interviews, the presence or absence of haptics was often discussed, and comments on the haptic aspect of the task were collated into a ‘haptics’ theme, with 97 items of data coded from 27 interviews. This theme included students talking about feeling the virtual objects generally, feeling haptic feedback during the diffusion of molecules and, conversely, not being able to feel haptic feedback at all. Two sub-themes emerged from the data from the ‘haptics’ theme: ‘concentration gradient’ and ‘not able to feel’, which will be discussed in Sections 4.3.1.1.1.1 and 4.3.1.1.1.2.

‘Haptics’ was identified as a major theme because it was largely populated (97 items of data from 28 interviews) and the haptic sense was integral to the research questions.

For the research questions to be answered, a functional haptic system needed to be developed to present complex information to students, and the students' opinions and comments on the haptic components of the activity gave insight into how well the system delivered the haptic sense during the learning activity.

The bulk of the haptics theme involved students describing their interactions with the virtual objects haptically. These descriptions generally involved heaviness, hardness, and resistance. For example:

"And like you could feel like how heavy they were…like which ones where heavier and bigger." – Mila

"So when you were trying moves things, you could actually feel the resistance." – Ariel

"Yeah and you could feel how hard or soft something was. And that was cool. And how heavy it was. And how stuck to something else it was." -Mikayla

Comparing the interviews from students in the haptic and non-haptic conditions, comments that were coded into this theme came more often from those in the haptic condition (63 items of data from the haptic condition and 34 from non-haptic). Additionally, those in the haptic condition used more haptic words in their comments (e.g. hard, soft, squishy, resistant) (18 from the haptic condition and 9 from the non-haptic condition), suggesting that those in the haptic condition received the haptic information intended for them.

The 'haptic' theme suggests that students could feel the haptic feedback being provided by the system and differentiate between the different feedback being given (weight, resistance, or hardness). Most references to the haptics referred to the haptic feedback provided when manipulating molecules in the virtual world, which involves physical manipulation and therefore may make use of the haptic processing channel at a basic level. The most complex concept demonstrated in the task, however, was diffusion and the concentration gradient across the membrane, which constituted as its own sub-theme described in the next section (4.3.1.1.1.1)

4.3.1.1.1.1 Concentration gradient

Although most discussions about the haptic content revolved around the properties of the molecules and how they moved, a smaller number of students also discussed the resistance from the concentration gradient provided when moving molecules across the membrane (10 items of data were coded from 6 separate interviews). Some examples of this are shown below:

"Yeah, the glucose was really interesting and the more you had, the more resistance the cell membrane gave. So… Yeah, that was good, I liked feeling that." – *Mikayla*

"When it was balanced on each side and imbalanced and it was harder to move them through, like so how the resistance can change depending on how many there are outside or inside the cell." -Declan

It should be noted also that almost all the comments coded to this sub-theme came from students in the haptic condition (9/10 items of data), which was expected, as they were the group provided with haptic feedback. This sub-theme shows a pattern of discussions of the concentration gradient, but it was clear from the interviews that the concentration gradient haptic feedback was not always noted or discussed as frequently as other haptic feedback found in the model (e.g. the weight/hardness of molecules and the membrane).

Diffusion and the concentration gradient are known to be difficult to understand in cell biology (Section 2.1.2.1.2) and are topics where haptic information (in the form of the forces acting on the molecules across a concentration gradient) is most suited for increased understanding. However, there are reasons as to why the concentration gradient feedback may not have been as noticeable to students as other types of haptic feedback, including effects of visual dominance and cognitive load, which are discussed in more detail in Sections 5.3.1.1 and 5.3.1.3.

4.3.1.1.1.2 Not able to feel

Whilst discussing the haptic sense in the interviews, some students revealed that they did not feel aspects of the cell (14 items of data were coded). These comments were collated in the sub-theme 'not able to feel'. Looking further into the students who commented on the lack of haptic information, almost all instances came from students in the non-haptic condition (11/14 items). This means that the majority of those in the non-haptics condition reported not feeling any haptic information, further supporting the fact that students largely perceived that haptic experience intended for their conditions: those in the haptic condition were aware of the haptic information being provided and those in the non-haptic condition lacked haptic experiences.

The findings from the 'haptics' theme so far has suggested that the haptic information was noted by students in the haptic condition. However, there is also evidence that attention to this haptic information may have been dampened, reasons for which are discussed further in the discussion of the thematic analysis (Section 5.3.1).

4.3.1.1.2 Learning collaboratively

A prominent topic in the interviews was the collaborative aspect of the task. Students worked in pairs in the activity with both individuals having the chance to fulfil the role of pilot and co-pilot, making their collaboration in the task a prominent feature. Comments on the collaborative aspect of the activity were collated in the ‘learning collaboratively’ theme, which was the most populated theme of the dataset (321 items of data across all 31 interviews). All students responded that they enjoyed working collaboratively in the activity, showing an overwhelming preference for collaborative work in this case. The reasons for this, and their opinions on the collaborative aspect of the activity, can be explored using the sub-theme ‘communication and discussion’ which is discussed in Section 4.3.1.1.2.1.

Comparing discussions about collaborative learning between students in the haptic and non-haptic conditions, more items of data in this theme came from the non-haptic condition (131 items from haptic students and 190 for non-haptic). Students in the non-haptic condition provided more discussion on the collaborative aspect of the task, suggesting that learning collaboratively may have been a more pertinent aspect of the task for them compared to those in the haptic condition. A possible reason for this discrepancy may be that those who did not receive haptic feedback needed to collaborate more in their task. The questions on the main study worksheet were worded to encourage discussion on how certain tasks felt, asking the students to describe what they thought they could feel at different intervals. As the non-haptic group did not experience haptic feedback, it may be that the pairs in this condition needed to discuss and communicate more to make sense of the questions and prepare answers. Additionally, it may be that the pairs in the haptic group communicated less, due to the distracting effect of the haptic feedback on the pilot, although there did not seem to be a difference in the two conditions in the ‘distraction’ theme discussed in Section 4.3.1.2.7.1. Whether or not the students in the haptic and non-haptic conditions collaborated more during the activity is beyond the scope of this thesis but may be useful for analysis in further studies.

4.3.1.1.2.1 Communication and discussion

A popular discussion topic on why students enjoyed working collaboratively was the use of communication and discussion to work out answers and make sense of the material. This resulted in a sub-theme, within ‘learning collaboratively’, named ‘communication and discussion’. Sixty-nine items of data were coded to the communication and discussion sub-theme from 25 separate interviews. Having someone else’s perspective and the use of two minds instead of one was often expressed as an advantage of working collaboratively in this task.

During the early stages of coding, a separate theme was developed named ‘negotiating meaning’. The ‘negotiated meaning’ code included dialogue between the pairs during the activity involving the negotiation of the meaning of what they saw and felt. However, as coding continued and developed, it was clear that comments coded to the ‘negotiating meaning’ theme was more accurately describing the communication and generation of ideas through discussion, and so this theme was merged into ‘communication and discussion’ in the reviewing stages of the thematic analysis. Some examples of statements coded into the ‘communication and discussion’ theme highlighting the use of communication to generate ideas are shown below:

“'Cause like I was kind of struggling for ideas, so then, like, Serena also had ideas, so Serena, when Serena said something, that kind of inspired me to think of something else. So that was good.” – Adalyn

“You could learn from each other as well not just from the, uh, the VR, cos like you can explain stuff to each other which would help.” – Gemma

“It gives two people's perspectives. I think that always helps because then you can, almost as a team, you can come up with an answer instead of just working on

your own and it's your opinion, you can combine each other's, and in the end it's probably a more accurate answer." -Hayden

The 'communication and discussion' theme suggests that working collaboratively helped students to discuss the learning material and support their learning by providing additional perspectives. Literature discussed in Section 2.4.4 suggests that in cognitively taxing tasks, collaboration may allow the use of two working memories to more efficiently process information (F. Kirschner et al., 2009a). This theme suggests that having another person to help discuss the activity with and help develop answers to complex questions was a factor in supporting students learning, and the presence of peer support may also help explain why students enjoyed the collaborative aspect.

4.3.1.1.2.1.1 Barriers to communication

Whilst talking about communication in their pairs, possible barriers to communication and their learning were also discussed. These comments were collated into a sub-theme under 'communication and discussion', called 'barriers to communication', containing 25 items of data. Some students expressed that the use of a head-mounted display and its effects on interaction between the pilot and co-pilot made communication more difficult than usual. For example:

"Well, it's quite hard to communicate what you want the guy to do, and when you're co-pilot he's got the headset on." – Shaun

"Kinda headset kind of blocks you out from the other person so you're kind of, like, zoned out." – Nikolai

“Well, you can't really, like, ask any, like, questions that much. Well, you could ask people around you, but that's not like... 'Cause they can't, like, know what you're seeing exactly, they don’t really know what you're feeling.” – Kelly

The use of the headset was quoted as being a possible barrier to communication due to the isolation of the pilot in the virtual world and preventing pilots from seeing their co-pilot as they spoke. There was also some discussion about communicating effectively as a pilot (see Kelly’s quotation), and the difficulty in communicating whilst simultaneously experiencing haptic feedback. Although the use of a head-mounted display had the possibility of creating barriers to communication, earlier pilot tests had found head-mounted displays more suitable than a desk-mounted option (Section 3.3.3), and the worksheet was designed for the main study to encourage communication despite the isolation of the pilot. From the ‘discussion and communication’ theme, it appeared students were generally able to communicate during the task, but a few students may have found it difficult to communicate whilst isolated with a head-mounted display or to communicate haptic information to their partner. This would correspond with the ‘transaction costs’ of collaboration described in Section 2.4.4, where additional resources are needed to communicate thoughts and ideas whilst working collaboratively. However, these costs are usually insignificant compared to the benefits of collaborating when learning complex information. Collaboration and transaction costs are discussed further in Section 5.4.3.3

In summary, students overwhelmingly expressed that they enjoyed collaboration in the task, and the data showed that the use of communication and discussion in generating ideas and supporting each other’s learning was present and preferable to working alone. Although some potential difficulties in communicating certain aspects of the experience were identified, it appears these were not widely experienced throughout the sample and the benefits of learning collaboratively seemingly outweigh the potential costs. The literature has suggested that collaboration may help the processing of complex information (F. Kirschner et al., 2009a), and students seemed to agree that sharing the workload was beneficial or preferable in this task.

4.3.1.1.3 Learning

As discussed previously (Section 3.4.8), the semi-structured interview included questions in two categories: the student's learning and their experience with the haptic device. For questions designed to explore their learning, students discussed various aspects of their learning in some detail. These aspects were found to be quite broad in topic, and so an array of sub-themes were included under the 'learning' theme. The prominent sub-themes identified under 'learning' were: 'learning by discovering and interacting', 'increased understanding', 'subverting expectations', 'retention/memory', 'membrane channels' and 'molecule shape and size'. These themes will be discussed in turn.

The 'learning' theme was selected as a major theme as it was largely populated (115 items of data) and present in all interviews. Additionally, students' views on their own learning and qualitative evidence of increased understanding can be used in conjunction with the quantitative results to provide a more accurate and complete picture of the findings.

Overall, the number of items coded to the learning theme did not differ largely between interviews from students in the haptic or non-haptic condition (59 items from the haptic condition and 56 from non-haptic). This supports the ANOVA (Section4.2.5), which showed no significant difference in the effects of haptics or no haptics on students' increase in cell knowledge test scores.

4.3.1.1.3.1 Learning by discovering and interacting

Whilst discussing their learning experiences using the system, students often commented on how interacting with the system and exploring in VR could allow them to discover and learn. Although these comments were often also coded as part of the 'comparison with regular teaching' theme (Section 4.3.1.2.4), they also encompassed a separate concept of interacting and discovering the cell model resulting in the uncovering of knowledge. These comments were collated into the 'learning by discovering and interacting' sub-theme, with 45 items of data coded over 20 interviews. The quotations below show some examples of items coded to this sub-theme:

If I wanted to see what was going on or something else that wasn't like entirely related to the question I could still like see what was going on when like maybe like the membrane proteins or something. – Mila

"When I was trying to figure out how to get the glucose to go through, like, I thought like cos the thing in the middle, cos the channel was opening and closing, then maybe something bigger should go through it like the glucose." – Ruth

"Because the ones that we, well, that I noticed, struggle to go through, they're bigger, so there'll be a lot more resistance." -Dustin

These quotations show some examples of perceived learning resulting from the exploration of the cell membrane. Mila discusses that by interacting and being autonomous in her exploration, she was able to explore aspects of the membrane outside of specific questions from the worksheet to increase her overall understanding. Again, this points to a more active and involved stance on the students' own learning. The quotation by Ruth explains how she discovered the function of the membrane channel by observing the protein and interacting with the glucose molecule, which serves as an example of hypothesis testing within the activity. As discussed in Section 2.4, TEL has been suggested to enable hypothesis testing in areas of science learning where direct manipulation of real-world objects is not possible (Rutten et al., 2012). The 'learning by discovering and interacting' sub-theme would suggest that the intervention used in this study was successful in facilitating hypothesis testing in cell biology.

The 'learning by discovering and interacting' sub-theme has shown that students not only enjoyed the interaction in the task (also evidenced in the 'comparison to regular teaching' theme) but also felt that they had benefited from the physical manipulation in VR which allowed them to explore the cell membrane, test hypotheses and take a more active role in their learning. This would suggest that a model which is able to be explored and manipulated, and a haptic device which mimics physical manipulation may support learning whilst using a haptic enabled device.

The next theme will further explore student learning by demonstrating students' perceptions of, or demonstrations of, increased understanding as a result of the intervention.

4.3.1.1.3.2 Increased understanding

The most populous sub-theme under 'learning' was 'increased understanding' with 111 items of data coded over 29 interviews. This sub-theme included any developments in their understanding as evidenced from their descriptions of the cell, or if they expressed that they felt their understanding had increased.

When students demonstrated increased knowledge, topics included the range of molecules present in cells, size/scale of molecules, the existence of channels, methods for molecules to travel across the membrane and, in some cases, the diffusion gradient across the membrane. Some examples of these expressions of increased understanding are below:

"I didn't really know about, like, that sodium, like potassium was in cells." -Adalyn

"I learned that glucose is bigger than oxygen and carbon dioxide molecules." - Serena

"That glucose needs a channel to go in and out of the cell membrane." -Ruth

"For example today, I just thought all, everything that the cell needed could go in and out and if the cell didn't need them then they would just not, it would reflect it off. But actually it, it allows it to pass through, though, and if it needs a channel then it'd have to go into the channel." -Charlotte

"Yeah, the glucose was really interesting and the more you had, the more resistance the cell membrane gave." -Mikayla

There are examples of students not only demonstrating increased knowledge of cell biology, but also explicitly expressing that they felt their understanding had increased whilst using the system, as seen below:

"I think it's just really a lot easier to sort of understand what's going on." – Caroline

"It just makes it a whole lot more interesting, and you kind of understand it a lot more. It just makes it a lot more helpful." Hayden

"I'll have a probably a better understanding than people who haven't done this because I've seen it, I've felt it." – Xander

The 'increased understanding' theme was largely populated and suggests that many students not only believed that they had increased their understanding, but also demonstrated their increased knowledge by stating what they had learned. This supports the quantitative result found in Section4.2.5, which showed that using the cell knowledge test, students overall increased their cell knowledge score after the activity. This interview data, however, indicates in which of the topics students had noticed a marked learning increase. Common subjects in which students expressed an increased understanding were the relative size and scale of molecules, the use of channels for some molecules and the free movement of others, and the existence of sodium and potassium ions in the cell. Although present amongst multiple interviews (6), the understanding of the effect of the concentration gradient across the membrane was not explicitly described as often as a topic of increased understanding. The changes in the true/false/unsure question answers from pre to post-intervention (Section 4.2.7) show that for questions relating to the concentration gradient, the most common occurrence was a correct answer both pre and post-intervention, suggesting that some students had conceptual understanding of concentration gradients before and after the activity. This did not reflect the majority of students however, and there was no clear evidence of increased understanding of concentration gradient according to the pre and post-intervention answers. The lower number of references to increased understanding of the concentration gradient in the interviews, coupled with the lack of evidence for learning of this topic in the cell knowledge tests, indicate that, generally, the concentration gradient was not a prominent topic in which students gained greater understanding in this activity. Comments from the students discussing their increased understanding of the size and relative scale of the different molecules supports the research discussed in Sections 2.1.2.1.1 and 2.1.2.1.2, which show that magnification, size and scale of cells and cell components are notoriously difficult subjects to understand and misunderstandings are common (Dreyfus & Jungwirth, 1988; Flores et al., 2003). As discussed in Section 3.4.2, the model in this study was scaled as realistically as possible, without compromising the ability for students to interact with it. Although compromises were required, the model was depicted more realistically than traditional representations, and so perceptions of increased understanding of size and scale after using this system suggests that more realistically scaled models may support learning in this domain.

4.3.1.1.3.3 Subverting expectations

Closely related to the ‘increased understanding’ sub-theme, the ‘subverting expectations’ sub-theme emerged as students spoke often about how what they saw and felt using the system conflicted with their preconceived notions about the cell. The result of these subverted expectations was often increased understanding, and so many in the ‘subverting expectations’ theme were also included in the ‘increased understanding’ theme (11 items of data in this theme out of 24 were also coded to ‘increased understanding’). However, this theme captures their increased understanding in relation to their misconceptions and expectations of the cell and shows how the activity challenged those notions. Some quotations from students discussing how their expectations were subverted are shown below:

“And also, the proteins, I didn't realise they were actually in the cell. I thought they were, like, in, like, inside the actual cell membrane. I didn't realise they were halfway in between.” – Dustin

“Yeah, and also it helps you feel sort of, so I didn’t know before that different molecules and atoms move differently with different resistance.” -Harrison

“And like when you see, uh, pictures of cells on the microscopes they're all sort of still, so I thought they moved very slowly, but actually it was very, very fast.”-Declan

“That they’re a lot more complicated than I thought they were in the first place.” -Ismael

These quotations are examples of the type of expectations that were challenged using the system, which included the speed and dynamic nature of the molecules in the cell, the positions of certain components and the differences between molecules in their movement. Other findings that were contrary to students' expectations included the presence of sodium and potassium (some believed that only oxygen, carbon dioxide and glucose were present in cells) and the need for glucose channels (2 students thought glucose would travel freely like oxygen). Students seemed to be generally aware of the free movement of oxygen and carbon dioxide, which is supported by students true/false/unsure test answers (Section 4.2.7), showing that many students were familiar with the role of oxygen in the context of respiration. According to this sub-theme, some students' expectations of the movement of glucose were challenged in the activity (8/24 items directly referenced glucose) and therefore challenged possible underlying misconceptions. This theme expands the 'increased understanding' theme by showing that certain expectations of the nature of the cell were directly challenged, often resulting in an increase in learning.

4.3.1.1.3.4 Retention/memory

Elaborating on the 'increased understanding' sub-theme, not only did students perceive that they had increased their learning by using the system, many believed that they would be able to remember the material more easily in the future. These comments were collated into the 'retention/memory' sub-theme, which contained 43 items of data across 17 interviews. Some students expressed that the knowledge they were acquiring through using the system would 'stick in their head' or that when they needed to retrieve the information later that they would be able to do so. Some of these comments are shown below:

"It kind of impacted in my brain." – Ariel

“I won’t forget that ever. I’ll never forget what that… It’s going to be in my head all day, all tomorrow, all, you know, the rest of this week and I’m not going to forget that little wall there and all the molecules moving around.” – Mikayla

“I feel like it's gonna stay in my head longer 'cause I'm gonna remember this rather than just writing it out on a sheet of paper.” – Larry

The comments within this sub-theme show the students’ confidence in the memorability of the experience and how that might benefit their retention of knowledge. The ANOVA discussed in Section 4.2.5 showed that students successfully retained their knowledge, and therefore students’ perceptions that they would remember what they had learned was correct. Some of the reasons given by the students for their opinions on the retention of the learning material involved the interactive nature of the activity compared to regular teaching (explored earlier in Section 4.3.1.1.3.1), how fun or novel the experience was (Sections 4.3.1.2.3 and 4.3.1.2.1), or visually experiencing aspects of the cell and its processes (Section 4.3.1.2.2.1). Some examples ae shown here:

“I think it just sticks in your mind a lot more as well, cos actually it's like a lot more fun.” – Taylor

“Everyone likes to play god, it’s a lot more memorable than just somebody explaining and writing down in your books what this all means. It’s a visual experience that I think you cannot forget. It’s a lot more memorable than just normal lessons.” – Ali

“Well, I think that when you've used this system you've got a picture in your head of what a cell membrane diagram and how it all looks. So that when you come to

the exam you need to explain things. Um, it will be… You'll have a clearer image in your head of what you've seen and what you need to explain." -Thomas

These examples show that in addition to the system being fun and novel, many students describe the visual aspects of the system as reasons why they may remember the information. The quote from Thomas described how he believed the system has given him a clearer image of the cell in his head, and two other students also referred to keeping representations of the model in their head. This suggests that according to the students, the system may help visualisation of the cell and its processes, which has been shown in Section 2.3 to be an important skill in learning cell biology. Visualisation as a theme is discussed further in Section 4.3.1.1.4.

4.3.1.1.3.5 Membrane channels and molecule size and shape

From the discussions on what the students felt they had learned, two topics emerged frequently and were collated as the following sub-themes: 'molecules size and shape' and 'membrane channels'. Out of all aspects of the cell, these two topics were the most commonly discussed in the interviews by the students and therefore seemed to be the most prominent topics in which they perceived learning to have occurred ('molecule shape and size' contained 37 items of data from 19 interviews, and 'membrane channels' 40 items over 19 interviews). This corresponds with the topics generally identified in the 'increased understanding' sub-theme, which also identifies the size and scale of molecules and the method of transport for glucose across the membrane as areas of increased learning. Below are some examples of quotations discussing the molecules shape and size and membrane channels:

"And a very clear comparison between different types of molecules." -Hazel

"If someone just reads it all out, I don't really understand it. But now I can visualise it, now I really understand all the different sizes." -Heather

"For example today, I just thought all, everything that the cell needed could go in and out and if the cell didn't need them then they would just not, it would reflect it off. But actually it, it allows it to pass through, though, and if it needs a channel then it'd have to go into the channel." – Charlotte

"Well, the fact that glucose has to have a channel to pass through otherwise it just, sort of, doesn't work." -Ali

It is apparent in the 'membrane channel' theme however, that a small minority did not identify the membrane channels successfully and had discussed the membrane channels without understanding their purpose. Instances that demonstrate this are shown below:

"I didn't actually notice that [the channel], but now I see it, I think I do realise that that was a channel." – Harrison

"I didn't notice [the channel], I didn't know what that was for. I know there was, like, the membrane protein… but I didn't think that was a channel." – Tristin

These were in the minority however, with only 4 students commenting on their confusion regarding channels. Other items of data coded to the 'membrane channel' sub-theme involved students discussing the glucose membrane channels in relation to their structure and function.

The 'membrane channels' and 'molecule shape and size' topics were prevalent in discussions on increased learning. However, these are topics which can be presented visually and without haptic feedback. The topic of the concentration gradient across the membrane was a topic integrated into the activity for which haptic feedback was especially suited. The concentration gradient (Section 4.3.1.1.1.1), however, was not as prominently featured in discussions of students' learning, which suggests that the concentration gradient may have been a less-noted feature of the activity.

In summary, the 'learning' theme has shown that students felt they had learned and demonstrated increased understanding of the topics overall. However, this increased learning did not differ by haptic or non-haptic condition, supporting the results of the ANOVA (Section4.2.5). Students stated that they enjoyed taking control of their learning experience by discovering and interacting with the model. Additionally, students were found, in some cases, to challenge some inaccurate preconceptions about the inner workings of the cell as shown in the 'subverting expectations' sub-theme. The 'retention/memory' sub-theme also showed that students believed that they would retain the information learned from the activity, which the quantitative analysis found to be accurate (Section4.2.5).

4.3.1.1.4 Visualisation

During discussions on the effects of the activity on their learning, some students commented on being able to see processes and components of the cell favourably. These comments would often refer to not having to imagine the content for themselves. The theme 'visualisation' collated these ideas, with 48 items of data included from 20 interviews. Comments coded to the 'visualisation' theme referred to being able to see structure or processes in the activity, rather than having to visualise (e.g. from a diagram). For example:

“It was like helpful to see it, like, from all dimensions kind of 'cause you could see it, like... 'Cause, like, when you look at a diagram of it, it's not that clear, but when you can, like, hold it and, like, turn it around, then it's a bit easier.” – Adalyn

“Well, because if you looking at it you can only imagine what it’s like, so you don’t actually know what's it's like for real.” – Declan

“It's a much easier idea to develop in your mind.” – Mathew

“If you just learn about it without VR or anything like that you can only just imagine it. So, you can’t get like a proper sense or anything. But with VR, um, as you can feel it you can get a much, um, you can get a better sense, like, you can actually imagine it properly.” -Jerome

These quotations describe how the system helped the students to visualise the learning content and build a better picture of the cell in their own minds. The literature has shown that visualisation is an important skill in learning complex topics in science, such as cell biology (Gilbert, 2005). This theme suggests that the system was successful in providing a learning environment that aids students in the visualisation of complex, unobservable phenomenon. Many students suggested that the cell model gave them a ‘better sense’ of the cell and its processes which allowed them to picture the content more easily in their own mind, (e.g. Jerome and Mathew’s quotations).

The ‘visualisation’ theme is more prevalent in interviews from those in the non-haptic condition (29 items from non-haptic, 19 items from haptic). The ‘liked features’ theme (Section 4.3.1.2.2) provides evidence the visual aspects of the activity may have been a more salient feature for those in the non-haptic condition compared to the haptic condition. With more non-haptic students discussing visualisation of the learning content using the system, the visualisation theme may support that claim. It is possible that those in the haptic condition had their attention split between haptic and visual information, and therefore did not comment as often on the visualisation and visual aspects of the system. In the context of their working memory, the haptic group had more information to process and therefore it is possible that increased cognitive load of processing haptic information may have lowered their attention to the visual aspect of the system compared to those in the non-haptic condition (further discussion on the effects of cognitive load in Sections5.2.1.3.1 and 5.3.1.1).

The literature suggests that using a model which can aid visualisation of complex information is beneficial for students learning (Section 2.3), and the 'visualisation' theme suggests that the system was successful in facilitating visualisation in the topic of cell biology and that the students found it to be helpful for their learning. Therefore, the presentation of learning content which aids visualisation may be a feature that can enable learning in a haptic interface system.

4.3.1.1.5 Difficulties

Although the interviews were mostly positive towards the use of the system, there were several issues that students identified, which were collated into the 'difficulties' theme. Difficulties identified were not homogenous, and sub-themes emerged including grasping particles, technical difficulties, thimble issues, task difficulty and space restriction. These will be discussed in turn.

4.3.1.1.5.1 Technical problem

During the experiment, technical difficulties were sometimes found to disrupt the student's activity. Occasionally, the system would freeze, or encounter a bug where the program would need to be rebooted to resume the activity. Sixty items of data were coded to this sub-theme, which was present in 21 of the 31 interviews, suggesting that most students encountered a technical problem during the study. These quotations demonstrate a few of these occasions:

“I think it's mainly that sometimes you had to press escape when you got stuck and things like that, I think that's really, uh...” – Erika

“Yeah, yeah, the blocks and side space. Sometimes it stopped working and you had to then press escape and then come back onto it again. We had to do that quite a few times.” – Gemma

“Probably, sometimes with the haptic feedback, the, um, it wasn't calibrated in the correct way. So sometimes you'd have a thumb, the thumb part, miles away from the other finger and it was quite hard to grab some things because they could be at different places.” -Hayden

These quotations show that the students found these technical problems to be noteworthy. However, reviewing the worksheets showed that most students reached the either the last or second to last question (26/33 pairs) (Appendix RR), indicating that any technical problems they may have encountered did not affect their ability to complete the activity within the timeframe.

4.3.1.1.5.2 Thimble issues

Another common issue that may have disturbed the students’ activity were problems with the thimbles on the haptic device. The thimbles were the connectors that attached the students’ fingers to the haptic device allowing them to interact with the virtual space. Despite the development of the thimbles through the feedback collected during pilot testing (Sections 3.3.5.2.1, 3.3.6.1.1 and 3.4.2), the vibrations and movement caused by the haptic device sometimes led to students’ fingers detaching from the thimbles, requiring assistance to reattach and disrupting the activity. Thimble issues were reported by multiple students (21 items of data were coded here from 12 interviews), examples of which can be seen below:

"My fingers kept coming out of the things." – Britney

"Yeah. We spent like five minutes each time just attaching it again." – Mila

"With the fingers as well, like, how they kept coming off and you need to know like to press escape and come back onto it." – Gemma

Most issues with thimbles involved female participants (16/21 items of data belonged to females), suggesting that it may have been more of a problem for smaller fingers. In addition, this theme contained more items of data from interviews in the haptic condition (17 non-haptic and 26 haptic), and so it may be possible that the increased haptic feedback and movement in the haptic condition may have increased the chance of thimbles slipping away from fingers. Whether the haptic or non-haptic conditions had a significant difference in the time disruption resulting from thimble issues may be explored further with video analysis of the activities, which is outside the scope of this project. However, there was little difference between the haptic and non-haptic conditions on the completion of the worksheet, with an average of 13.2 questions completed in the haptic condition and 12.9 for the non-haptic condition (Appendix RR). The comparable completion of the worksheet in both conditions would therefore suggest that any technical difficulties did not disproportionately affect students in either condition in their ability to complete the task.

4.3.1.1.5.3 Task difficulty

Discussing what they found difficult whilst using the system, some students commented on the difficulty of the task, although these were in the minority (30 items of data were coded from 12 interviews). The students were guided in their task with a worksheet which instructed them to write answers to questions based on their interactions with the cell. Some students found the task to be quite difficult, as evidenced below:

"Some of the questions we didn't know how to answer." – Ruth

"Yeah, they [the questions] were quite, like, really like long and you get confused cos there were lots of questions in one, so you would think where should I start with this." – Scarlet

"Yeah, we were a bit confused, we were a bit confused on how cos we didn't really learn that, we were a bit confused on how it would change, um, if there was more in than outside." – Lea

"Answering the questions, they were quite difficult." – Calum

More specifically, a few students commented that they would have preferred additional or more detailed instructions (5 items of data from 4 interviews):

"And if you had maybe some more kind of directions in the machine, like maybe like something at the edge, like telling you what to do. Or like directing you to certain bits to make it more learning element rather than just playing around with it." – Nikolai

"I didn't know that, so I figured it out. But maybe some more instructions to tell us to start with." – Mikayla

Those who discussed needing more instructions to guide them in their activity often also suggested that they were uncomfortable with free exploration without a clear goal or learning aim set out beforehand. This can be seen in Nikolai's comment about wanting to be directed instead of 'just playing around', and Mikayla's comment about wanting more instructions after having to figure something out by exploring. This suggests that some students were uncomfortable with a less-directed learning activity which prioritised exploration. From the 'preference for interaction' and 'learning by discovering' themes, it has been shown that many students enjoy taking agency over their own learning and experiencing the learning content for themselves, but this theme may suggest that some students are less comfortable with this idea.

Other students commented in a similar way to Mathew, who thought the questions were quite long, which added difficulty to the task. This suggests that the format of the questions for some may have taken additional concentration to process them. The effort needed to decipher the questions and construct answers could have added avoidable cognitive load to the task. However, as students were found to increase their cell knowledge overall (Section4.2.5), the perceived difficulty of the task did not seem to hinder students in their learning.

Additionally, Lea's quotation above refers specifically to questions regarding the centration gradient. Lea's comment suggests that she was unsure of the concept of the concentration gradient and the system did not seem to help them increase their understanding. As discussed in Section 4.3.1.1.1.1, there is evidence that the concentration gradient haptic information may not have been as noticeable to students as other types of haptic feedback from the system, which may offer an explanation for Lea's experience. The perception of the concentration gradient haptic information is discussed in more detail in Sections 5.3.1.1, 5.3.1.3 and 5.4.1.1.1.

Comparing students from the haptic and non-haptic conditions, there were more items of data present in the 'task difficulty' theme from those in the haptic condition (29 items of data from haptic students and 9 from non-haptic). Therefore, it is possible that students in the haptic condition may have found the task more difficult than those in the non-haptic condition. This could be because they were exposed to additional haptic information during the task, increasing the amount of information to be processed.

Overall, students stating that the task may have been difficult suggests that the task could have been challenging enough for the beneficial effects of collaborative learning to take effect. The effects of collaboration on cognitive load was discussed in Section 2.4.4, where the literature showed that collaboration on difficult learning tasks may allow students to split cognitive load across both their working memories, thus allowing for easier processing of information (F. Kirschner et al., 2009a). However, the literature also suggested that if the task was relatively easy, then the cognitive load needed to collaborate with another person would outweigh the usefulness of collaboration in completing the task overall (F. Kirschner et al., 2009b). Therefore, this sub-theme may suggest that the task was challenging enough to utilise the positive effects of collaboration in learning complex concepts in this study.

4.3.1.1.5.4 Grasping particles

After technical problems, the most discussed difficulty with using the system was grasping the particles in the virtual space (43 items of data coded from 22 interviews). Many students expressed that grasping certain particles was difficult for them. For example:

“Yeah, it was difficult to, like, hold things kind of.” – Adalyn

“It was easy to move the glucose but it wasn’t very easy to getting hold of it.” – Mikayla

“Yeah, it was often very hard to try and actually grab the particles.” – Gemma

"I found that quite hard because you can't really get hold of them too well." - Sheldon

This was a novel system for the students and an unfamiliar way of interacting with virtual objects, which may explain why students found this action difficult. Without previous practice on the system, the controls were still novel and although most movements required for manipulation in the virtual space were intuitive, grasping the molecules was discussed in many interviews to be more difficult.

More students in the non-haptic condition discussed problems in grasping particles (17 items from the haptic condition, 26 from non-haptic), which suggests that the lack of haptic feedback may have inhibited these students more often from handling the molecules. Grasping molecules was discussed as a difficulty in most (22/31) interviews, and it is possible that this difficulty may have increased the amount of extraneous cognitive load on the students' working memory, possibly more so for non-haptic students. As discussed in Section 2.4.2.1, extraneous cognitive load is provided by the way in which information is presented and as extraneous load increases, fewer resources are available in the working memory to facilitate learning. Taking this into account, it is possible therefore, that using a novel complex system to deliver complex learning content without sufficient practice may unnecessarily add extraneous cognitive load and hinder learning.

4.3.1.1.5.5 Space restriction

An additional difficulty mentioned by students was the restriction of the space in which they were able to move their hands to control the cursors in the virtual world. 17 items of data were coded to the 'space restriction' sub-theme over 10 interviews, which although notable, suggests that it was not an issue for most students. Although the students were able to move their fingers around freely in the VR environment, the physical space they were able to do so was limited by the frame of the robotic arms. This meant that students could only reach out a certain distance before hitting the frame and having to readjust. Some quotations describing this as an issue are shown below:

“Yeah, if you had a bigger space is what I mean. Maybe … So the restriction on the fingers that you had, I think if you’d been able to take them out a bit wider and forward and backwards a more, you would have been able to pick up more things.” – Mikayla

“…because sometimes when you would try and grab one it would like go more further back to which the machine couldn’t stretch that far.” – Scarlet

“Like the thing next to the bit where you but your hands, I'm not sure what it's called, it's like a arc thing, it got in the way.” -Harley

This theme may be connected to the ‘grasping particles’ theme, as some students connect the restriction of space to move to not being able to reach further in the virtual space to grab particles out of reach. Again, if students were dedicating resources to figure out how to manoeuvre the system to grasp particles, it may be that these are resources that are not directed towards understanding the learning content.

4.3.1.1.5.6 Summary

In summary, the ‘difficulties’ theme highlighted the aspects of the students’ experiences which they found to be difficult. This included dealing with technical problems such as freezing and mechanical issues such as fingers becoming unattached to the thimbles. Difficulty grasping particles within a restricted workspace was also highlighted as an issue. However, these issues were not so severe that they stopped students from learning from the system, as the cell knowledge test has shown that, overall, students did increase their knowledge (Section4.2.5). However, these difficulties were prominent enough for some students to mention in their interviews and therefore should be considered as a possible source of unnecessary extraneous cognitive load which has the potential to impact learning negatively. Potential sources of extraneous cognitive load identified in the thematic analysis are discussed further in Section 5.3.1.1.

4.3.1.2 Minor Themes

4.3.1.2.1 Praise for the system

A salient point found throughout out the interviews was that the students generally liked learning from this system. Evidence for this is revealed in the theme ‘praise for the system’ which contained 128 items of data over 27 interviews. ‘Praise for the system’ documented expressed enjoyment or fun using the system, or where students explicitly described using the system as a good experience. This theme encompassed expressions of enjoying the system or being engaged by the activity and often used the words ‘fun’ and ‘cool’ and ‘interesting’ when describing their experience. Explicit expressions of enjoyment were common, as seen in the quotations below:

“I really enjoyed it.” -Erika

“Yeah. I think it just sticks in your mind a lot more as well, cos actually it's like a lot more fun.” -Taylor

“I feel like it’s a lot more fun, a little more interesting….It was really cool.” – Karla

“It was just generally quite fun.” -Kelly

These examples were typical of the reactions of the students, and others went further to express a heightened interest, indicative of engagement in the task:

"It holds your attention well." – Gemma

"…and it's quite interesting, like, you won't fall asleep during." -Samara

This theme suggests that generally, the students enjoyed using the system and that it was a positive experience. As discussed in the literature review (Section 2.4.2.2), there is evidence that enjoyment of a task may make students more likely to invest in germane cognitive load for their learning (Van Merriënboer & Sweller, 2005). The analysis of the transcripts therefore suggests that from an enjoyment point of view, the system was engaging enough that the students may have been inclined to invest germane cognitive load to the tasks. In context of cognitive load overall, this means that students may have been dedicating their working memory resources to create and draw from existing schemas to process information into long term memory. Although this increases cognitive load on working memory overall, it is also necessary for learning (Ayres, 2006).

Comparing the amount of data coded to this theme from students in the haptic and non-haptic conditions, there were more expressions of praise in the non-haptic condition (53 haptic and 75 non-haptic). This may suggest that the students in the non-haptic condition enjoyed the task more overall. Although the reasons for this may not be immediately apparent, other themes in the data suggest that students in the non-haptic condition discussed liking the visual aspects of the system more often (discussed in Section 4.3.1.2.2.1) and those in the haptic condition may have found the task more difficult (Section 4.3.1.1.5.4) which may have had an effect on the students' enjoyment or expressions of enjoyment of using the system.

Although the ‘praise for the system’ theme shows that the students had favourable opinions of the system overall, which features in particular they liked can be explored further in the theme ‘liked features’, which is discussed in Section 4.3.1.2.2.

4.3.1.2.2 Liked features

Whilst discussing their opinion of the system, students revealed features which they particularly liked, many of which were shared across the sample. Patterns of liking particular features were collated in the ‘liked features’ theme, which contained 161 items of data recorded from all 31 interviews. This theme incorporated sub-themes to identify the categories of features which were repeatedly expressed by students to be a liked feature. These sub-themes were identified as ‘seeing’, ‘moving things’, ‘feeling forces’, and ‘feeling in general’.

4.3.1.2.2.1 Seeing

The most commonly liked feature expressed by the students centred around the visual features of the system and was named ‘seeing’ (75/165 of all items coded to ‘liked features’ were coded to the ‘seeing’ sub-theme). The ‘seeing’ sub-theme described any expression of liking what they could see in the system, or liking being able to view the processes and components of the cell membrane model. The interviews contained several expressions of liking the visual aspects of the system, as shown in the quotations below:

“Carbon dioxide can just go straight through and come out and it is also good like being able to see it visually.” – Charlotte

"I thought it was so cool, like, um, just like looking around, it was seeing everything in 360." – Lea

"It's a completely different way of looking at it instead of just looking at models and things, it's a lot more real in a sense. You see it in more detail as well." – Hayden

"I found it quite nice to see it visually, like a picture in 3D, 'cause it makes you see it clearly." – Nikolai

"It was quite interesting seeing it from different angles." – Christopher

"It was quite cool how you could actually see it huge and up close and in reality it's really tiny." -Ivy

As seen from these example quotations, an aspect many students found positive was seeing in 3D compared to 2D. As discussed in Section 2.2, the translation of 2D to 3D has been suggested to be an important spatial concept in successful STEM learning (Taylor & Hutton, 2013; Wu & Shah, 2004), and the prominence of discussion around the 3D nature of the model suggests that this system may have been able to facilitate the conception of 3D cell components.

Most of the items of data found in the 'seeing' sub-theme were from students in the non-haptic condition (51 out of 71 items of data). This may be because the non-haptic condition did not have the haptic feedback to discuss in the interviews, and therefore the visual aspect of the task would have been the most salient feature for them. Another possibility is that the haptic group did not pay as much attention to the visual aspects as they also had haptic feedback to process and direct their attention to (Section5.2.1.3.2).

4.3.1.2.2.2 Moving things

Many students also expressed that they liked being able to move things within the system. The 'moving things' sub-theme contained 37 items of data from 16 interviews. Below is an example quotation of a student expressing their preference for moving things in the system rather than being told what would happen:

"Yeah, if you look at a diagram and you're told, well, oxygen can move freely, you don't necessarily take that in as much as if you actually could pick it up and move it, and you can see that it can move pretty freely." – Xander

This quotation, and others in the sub-theme, demonstrate that the interactive act of moving objects within the virtual space was appreciated by the students. Xander's comment also touches on a preference for interaction, which is discussed in Section 4.3.1.1.3.1.

4.3.1.2.2.3 Feeling in general

Concerning the physical aspect of the system, the interviews showed a general like for being able to feel in the virtual world. These expressions were collated into the 'feeling in general' sub-theme within 'liked features'. The quotations below demonstrate students commenting on their appreciation for the haptic sense generally, whilst exploring in the system:

"I liked that, like, when you touch something, it kind of felt like you were actually touching it." – Adalyn

"It is really cool…you can actually feel the objects that you, you touch and it's, it's not like in a computer." -Audrey

These quotations suggest that the physical manipulation aspect of the system, which allowed exploration in the model, was appreciated generally. However, there were no differences in the number of items coded to this sub-theme between the haptic and non-haptic conditions (both conditions had 9 items of data coded to the sub-theme). This suggests that some students in the non-haptic condition described their manipulation of the cell model with ‘feeling’ words, despite the lack of haptic feedback. Comments from the non-haptic students referred to being able to ‘touch’ things in the system, which they enjoyed. As discussed in Section 2.4.2.1.3, several studies showed that physical manipulation can have an advantageous effect on children’s mathematical and scientific learning (Bara et al., 2004; Glenberg et al., 2004; Zacharia et al., 2012). Possible explanations of this effect include the use of the haptic channel allowing for more efficient information processing (discussed in Section 2.3.3) and the use of embodied cognition providing anchors for understanding abstract concepts (discussed in Section 2.4.2.1.3). Therefore, in addition to students enjoying interaction over passive learning, it is possible that the act of physically manipulating the cell model in VR may have a beneficial effect on students’ learning. If so, this suggests that the students in the non-haptic condition may have still benefitted from their manipulation of the cell model due to the physical manipulation and their enjoyment of being able to ‘touch’ things in the system.

4.3.1.2.2.4 Feeling forces

Several students also commented specifically on liking the feature of feeling forces within the system. These comments were collated into the ‘feeling forces’ sub-theme, which contained 16 items of data coded from 5 interviews. This includes the feeling of the drag forces across the membrane relating to the concentration gradient. The quotations below show examples included in this sub-theme:

“So when you were trying moves things, you could actually feel the resistance.” – Ariel

“Yeah, the glucose was really interesting and the more you had, the more resistance the cell membrane gave. So… Yeah, that was good, I liked feeling that.” – Mikayla

The ‘feeling forces’ sub-theme emerged as the coding process developed but was not as broadly prevalent across the sample as the ‘feeling in general’ sub-theme. Almost all items of data in this sub-theme originated from the haptic condition (14/16), which is expected, as only the haptic condition included forces in the feedback. This theme suggests that although not every student in the haptic condition mentioned feeling forces, the forces were distinguishable and noted positively by some in the haptic condition. Additionally, this theme shows that as intended, forces were not generally perceived by those in the non-haptic condition.

The ‘feeling in general’ and ‘feeling forces’ sub-themes showed that students enjoyed feeling the cell model. Additionally, the ‘learning by discovering’ and ‘interacting’ theme showed that students enjoyed interacting with and manipulating the learning material first-hand. These themes may be relevant to the embodied cognition theory discussed in in Section 2.4.2.1, which suggests that understanding is constructed by information represented within the sensory and motor systems. Embodied Cognition theory suggests that touch feedback can become a cognitive anchor for understanding abstract concepts and building schemata of haptic information, grounded in the haptic sense. In this case, students who expressed liking interacting and feeling forces themselves, according to the Embodied Cognition theory, may have taken that haptic information and embodied it into their multi-modal understanding of an abstract and complex subject. However, this study cannot determine whether the information from the haptic system was embodied. Additionally, the mixed ANOVA discussed in Section 4.2.5 showed that those in the haptic condition did not show a significantly larger increase in learning compared to the non-haptic condition and so, although the ‘feeling forces’ sub-theme was mostly populated by the haptic condition, this did not translate to better knowledge scores or recall, as the embodied cognition theory would suggest.

4.3.1.2.2.5 Summary

In summary, the most commonly discussed liked features in the interviews were the visual aspects of the system and being able to move things within the model. Students were also found to enjoy feeling in general and feeling forces specifically during the activity. Visual aspects and moving things being identified as the most common liked features was expected, as these were aspects experienced by all students, whereas forces would have only been experienced by those in the haptic condition. Overall, this theme expands on the ‘praise for the system’ theme by giving examples of what students liked specifically about their experience. Although the most common liked features were visual (which can be also be provided by animations and other 3D learning systems) many students also specified manipulating objects in the virtual world and feeling things and forces as liked features, which are specific to a haptic system. The ‘praise for the system’ and ‘liked features’ themes suggest that this project was successful in creating an appealing learning tool capable of providing rich visual and haptic feedback. According to the literature, providing rich 3D visuals, multi-sensory feedback, physical manipulation and providing an interesting or engaging task can benefit learning in science, and therefore the themes discussed so far suggest that integrating these concepts into a haptically-enabled interface can support learning.

The next theme ‘novelty’ will expand on what the students thought about the system in relation to their experience, or lack of experience of similar technology or learning practices.

4.3.1.2.3 Novelty

Some students commented that the system was different or new and that this was a novel experience for them. These comments were collated into the 'novelty' theme, which included 16 items of data coded from 9 interviews. The novelty of the system was often discussed in relation to the activity being more memorable than usual methods of learning and in relation to the excitement of a new experience. In some cases, the novelty of the system was also discussed in relation to how the benefits of novelty may wear off as frequency of use increases (4 items coded suggested this). Some examples of students describing the novelty of the system as a benefit to learning are shown below:

"I think it's just because learning is just boring, whereas VR is something that's quite new so it's exciting for people." – Rose

"Cos it's not something you do, like, often, so it's more exciting." – Gemma

In these quotations, novelty is linked with excitement and enjoyment (which is also discussed in the 'praise for the system' theme), but novelty was not always described as a lasting positive attribute. For example:

"I think it would get, um, for me, personally, I think it would get a bit, um, a bit kind of boring…like if it was really frequently." – Scarlet

"It's something you don't have every day. So if I did it for every subject, I'd probably not get bored of it but to have that, I wouldn't learn as quickly with it." – Natasha

In these quotations, the students predict that as the novel aspect of the system subsides with frequent use, the benefits of the system would decrease. The literature suggests that a novel way of presenting information such as the system used in this project exerts extraneous cognitive load on the student as they navigate how to use the system and make sense of the information simultaneously (Sweller, 1994). With continued use therefore, it is theorized that the extraneous load from the novel system would decrease and lower the cognitive load overall. However, from the students' perspective, the novelty of the system introduces more motivation to interact with the learning content, which may decrease with repeated exposure. This may be the case, but CLT (Sweller, 1994) would suggest that as novelty decreases, the potential for learning more complicated content may increase as more working memory resources are freed from extraneous load. Additionally, there were some students who discuss that the novelty of some aspects of the system had a distracting effect (discussed further in Section 4.3.1.2.7.1), which may subside as the novelty declines.

4.3.1.2.4 Comparison with regular teaching

During the interviews, students were asked for advantages and disadvantages in using a haptic system compared to their regular way of teaching. This highlighted several points in the students' opinions on what the learning environment could do to improve regular teaching and what they would consider as downfalls of the system compared to their regular lessons. Items coded to the 'comparison with regular teaching' theme came from all interviews (170 items coded from 31 interviews). Most often, using the system was compared to looking at a diagram or being told information by a teacher:

"You're doing something yourself rather than just a teacher always telling you."- Britney

"While in the classroom you actually just get told what happens and you don't actually see it physically happening while in the VR you can like experience." – Luka

It was also revealed that using the system may be preferable to normal teaching as it was thought to keep the students more interested in the learning topic, as seen in the example quotations below:

"In class you get really bored, like really easily…So it was more, it kind of kept your focus going a bit more." – Scarlett

Compared to sitting in a lesson, for example… you are sort of interested by it and you wanted to explore, whereas sort of being quite bored in a lesson or disconnecting from what the teacher is saying. – Harrison

Because it's quite hands on, you're not wasting, like, so you're not getting bored because you're just looking at a book. -Dustin

Students' discussions on the comparison of their activity with regular teaching methods suggested that the use of a collaborative, 3D learning environment in their learning was preferable. As coding progressed, reasons for their preference began to emerge, which were collated into the sub-themes described below (Section 4.3.1.2.4.1).

4.3.1.2.4.1 Preference for interaction/experiencing for themselves

As more students' views on using the system compared to their regular teaching were revealed, a sub-theme emerged named 'preference for interaction/experiencing for themselves', which was a popular talking point. In this sub-theme, students suggested that actively interacting with the cell model whilst learning was a positive attribute, in comparison to a more passive learning experience.

"Like, you could actually interact, like, you weren't just answering questions, like you could do stuff with it." – Mila

"I think the thing is with this is it's a lot more interactive. Um, in the class it's always the classic, it can get a little bit boring after a while." – Hayden

"I prefer it more than a microscope because you can interact with it more." – Harley

This sub-theme also included various quotations discussing the fact that using the system allowed the students to experience the learning material themselves rather than be given the information 'second hand' in a passive manner. For example:

"You're doing something yourself rather than just a teacher always telling you." – Britney

"Yeah, like as good as the teachers are, like, they're really good at teaching, they can't actually show you or help you like, like feel the way that, like, the programme did." -Scarlett

"You can see for yourself what is being explained rather than, your teacher telling you and then having to write it down and then trying to remember it." – Shaun

These findings suggest that students enjoyed taking ownership over their own learning, by observing and experiencing it first-hand and learning directly, compared to receiving information passively. As discussed in Section 2.4.4, it is possible that by taking ownership of their learning experience, students may be more likely to invest germane load to process the information (Vandewaetere & Clarebout, 2013). Additionally, this theme shows that students usually compared the intervention to diagrams or information given by teachers to compare, which are abstract representations. It has been argued that a departure from a more traditional, abstract representation in the classroom to a more concrete model able to be explored by students directly, could help transform these abstract concepts to concepts that are more easily understood (Section 2.4.2.1.2). As discussed in the literature review (Section 2.1), cell biology is notoriously difficult for students to grasp because of its abstract nature (Dreyfus & Jungwirth, 1988), so if students believe that their understanding of abstract concepts increased by interacting with the learning material themselves (as the ‘preference for interaction/experiencing for themselves’ sub-theme would suggest), then this would be a positive attribute of haptically-enabled systems for learning cell biology. Although the ANOVA did not find a significant effect of the condition on the learning of the students (Section 4.2.5.2), this theme suggests that students preferred their learning experience in this study compared to regular teaching methods, and that interaction itself may have provided a positive effect on learning. This corresponds with previous literature, which suggests that key to the understanding of cell biology is the ability to model abstract and complex content regarding the molecular world (Tibell & Rundgren, 2010).

4.3.1.2.5 Value for difficult subjects

Discussing the sub-theme ‘preference for interaction/experiencing for themselves’, students often commented that they preferred interacting directly with the learning content. It was discussed in Section 4.3.1.2.4.1 that interacting directly may help transform abstract concepts into more a more concrete state to process more easily. Another theme that may support this assertion was ‘value for difficult subjects’ which included 5 items of data from 3 different interviews. This theme included comments about the system or activity being useful for difficult or complicated subjects or concepts. For example:

Maybe revision, like when we've done a topic or if you don't understand something… maybe like, occasionally, if someone's having trouble understanding. – Ruth

I feel like you could learn more complicated things on the VR and simpler things, like, CO^2 for me is very easy on the sheet. – Felicity

Findings in this theme show that some students perceived that learning simple, less abstract aspects of cell biology would be more efficient with traditional methods, whereas difficult concepts would be well-suited to using haptic feedback within a learning environment. This corresponds with the research discussed in Section 2.4.2.2, which suggests that the use of haptic feedback would be most useful for the learning of abstract concepts (Dreyfus & Jungwirth, 1989; Zacharia, 2015) which are known to be difficult for students to understand.

4.3.1.2.6 Easy

Despite some aspects of using the system being identified as difficult (demonstrated in the 'difficulties' theme in Section 4.3.1.1.5), students described most aspects of the system as 'easy'. Students discussed which parts of the system and activity they found easy, and their comments were collated into the 'easy' theme, which included 111 items of data collated from all 31 interviews. Overall, the most common aspects which students described as easy were viewing the cell, moving things in the model, and using the co-pilot controls (including adding and removing molecules). Some examples of these are shown below:

"Um, it was easy to like look around the space… Yeah, it wasn't hard to like switch from side to side or like lean backwards." – Charlotte

"Moving the oxygen and carbon dioxide was easy." -Ariel

"I found most… Well, if not everything, easy. The moving the oxygen and carbon dioxide molecules was probably side-to-side the easiest thing and looking around. That was easy." – Draven

"most of the stuff was quite easy." -Roberto

"I think the grabbing the particles, the molecules, and kind of pulling them, moving them around. I thought that was quite easy and looking around." – Scarlet

"Probably, like grabbing, like the, like the proteins and just dragging them around."- Johnny

Initially, there seemed to be some contradictions in student's opinions of the difficulty of the system between the 'easy' and 'difficulties' themes. In the 'difficulties' theme it was shown that grasping particles was a recurring difficulty faced by students using the haptic interface, but the quotations above from Scarlet and Johnny suggested that grabbing and moving the particles was easy for them. Overall however, 5 items of data in the 'easy' theme specified grabbing or grasping particles, which is a minority compared to those who specified grasping particles as difficult in the 'grasping particles' sub-theme.

Some students suggested that moving the particles was easy for them but did not specify grasping them (26 items of data), suggesting that grasping molecules may have been difficult, but moving them afterwards was easy. Supporting this, two students followed up their statements by explaining that moving was easy, even if grasping them was difficult to begin with. Quotations from these students are shown below:

"it was easy to move the glucose but it wasn't very easy to getting hold of it." – Mikayla

"moving the particles around was easy, but actually in the first place getting a hold of them was really hard." -Scarlet

Overall, it seems from analysing the comments included in the 'grasping particles' sub-theme and the 'easy' theme, what at first seemed like a contradiction was actually a distinction between grasping a molecule and moving it around the environment. Additionally, although some students found the worksheet/task difficult, one student contradicted this by describing it as easy to navigate:

"The instructions were clear as well, like following all the different cues and that, so that was easy to do was co-pilot." – Gemma

However, Gemma was an isolated case, as she was the only student to specify the ease of following the worksheet instructions.

Findings from the 'easy' theme and the variety of aspects which the students identified as easy, suggest that the activity overall was not overshadowed by previously discussed difficulties (Section 4.3.1.1.5), and that most students found the system generally easy to use.

4.3.1.2.7 Distraction versus focus

Reviewing the interviews, two themes were apparent in the students' descriptions of their use of the system, which appeared to be conflicting. These two themes were named 'distraction' and 'focus'.

4.3.1.2.7.1 Distraction

The ‘distraction’ theme included comments about the system distracting the students in any way from their learning. In this theme, a common distraction described was the visual stimuli experienced by the pilot through the head-mounted display. Twenty-six items of data were collated in the ‘distraction’ theme from 11 different interviews. Quotations from the interviews that demonstrate distraction are shown below:

“One person knows, you know, in the real world, can see all the question things the other person's really, like, amazed by the VR system and they did go really off-topic.” – Erika

“You probably could get carried away. You could end up wasting a lot of time just playing around with it.”-Dustin

“You do get a bit distracted in the VR.” – Larry

The ‘distraction’ theme suggests that the visual aspect of the VR may have a distracting element that can detract from the task, and that the visual stimuli were engaging and captured the students’ attention. As discussed in Section 2.4.5, the visual sense has been shown to dominate other senses and according to the directed-attention hypothesis, people usually direct their attention to visual information above other modalities. If the visual information is as appealing as the ‘distraction’ theme would suggest, this may have had consequences for the use of haptics in this system. The directed-attention hypothesis suggests that if attention is directed to visual information, there is a bias towards that modality and attention is less focused on information from other modalities, such as touch. Using this system, the visuals are the first sensory modality the students experience, and if the visual stimuli were as engaging as the distraction theme suggests, then it is possible that more attention would be focused on the visuals than the subsequent haptics. If less attention was given to the haptic information, then the proposed benefits of using the haptic processing channel may have been dampened, offering a potential contributing factor for the lack of significantly increased learning gains for the haptic condition in this study (Section 4.2.4).

4.3.1.2.7.2 Focus

A conflicting theme to ‘distraction’ was also present in the data: ‘focus’. The ‘focus’ theme included comments about being focused on the task or feeling more focused. Several students (14 items of data from 10 interviews) discussed feeling that using the system allowed them to focus more on the task than usual. For example:

“But this, whereas with this you only see like cell membrane. And I think it’s quite good because you can actually focus on that and you don’t... Don’t get distracted and then forget what you’re doing.” – Kadence

“Yeah and it was quite interesting, so compared to sitting in a lesson, for example, if you are, you are sort of interested by it and you wanted to explore, whereas sort of being quite bored in a lesson or disconnecting from what the teacher is saying.” -Harrison

Students whose comments were included in this theme seemed to express that because the system was interesting and grabbed their attention, they were more focused on the learning material. However, this is contrary to other students commenting that they or their partner were distracted by using the system. Looking at the context surrounding the two themes, it seems that those discussing distraction refer to being distracted from their learning goal or specific worksheet questions by the stimuli within the virtual space, whereas those who discuss being focused seem to imply that they were more focused on the system itself but not necessarily the learning material. For example, Dustin’s comments on being distracted refer to moving off topic by exploring further in the cell. Although this is a distraction from the worksheet or specific questions, he is still engaged with the cell model. Whereas in Kadence's comments about remaining focused in comparison to usual classroom activities, she refers to staying focused on the subject matter and not getting distracted from influences outside of the learning environment. These comments are typical of those from the 'distraction' and 'focus' themes, and together show that, although students feel like they could be side-lined from specific learning tasks within the system by the sensory stimuli available, students also feel that using the system allowed them to be more focused on the learning content as a whole, compared to normal teaching methods, where outside distractions are more common.

There may be consequences of the overlapping effects of distraction and focus on the students' abilities to learn from haptics. The 'focus' theme suggests that students feel interested and focused on the activity, which according to CLT (Sweller, 2011) may increase germane cognitive load, allocating more working memory resources to process the information (discussed in Section 2.4.2.2) . However, the 'distraction' theme suggests that the visual aspects of the activity are prominent and attention-grabbing, which as discussed earlier, may distract from other modalities such as touch.

4.3.1.2.8 Realistic

Whilst describing the model itself, a recurring theme in the data was how students described it as 'realistic'. Looking closer to the context of comments discussing the realism of the system, it seemed that students were mostly describing the manipulation, grabbing or movement of the molecules as realistic, as if they were really manipulating the components of the cell membrane. Ten items of data were coded into the 'realistic' theme, which came from 9 separate interviews. Here are some quotations typical of the theme demonstrating this:

"It's like the feeling, like, when you, like, grab a molecule it feels really like real that you're actually touching something." – Samara

"You could use your hands to move stuff and that it wasn't like using computer keys, it was as if you're actually in there." – Christopher

"I think because it looks like reality and it's much better than just a diagram where you can just see it, like when you can touch the things and try everything by yourself." -Jimmy

The basis of the comments included in the 'realism' theme was that students felt like they were touching or manipulating objects, regardless if they were in the haptic or non-haptic condition. As discussed in Section 2.4.2.1.3, physical manipulation can have a beneficial effect on scientific learning, which may utilise the haptic sensory channel to more efficiently process complex information, or use embodied cognition to anchor abstract concepts to concrete motor information (Zacharia et al., 2012) (Section 2.4.2.1 for more detail). Comments included in the 'realism' theme suggest that students feel they are getting a realistic experience of manipulating objects in virtual space.

4.3.1.2.9 Misunderstandings

Throughout the interviews, it became apparent that some students either had picked up misinformation or had underlying misunderstandings that were not corrected by using the system. Comments describing misunderstandings or misinformation were collated into the 'misunderstanding' theme, which had 30 items of data coded from 17 interviews. Most evidence of misunderstandings occurred where students were discussing what they had learned from the activity or in describing the what they had seen. For example, a few students (9/30 items of data) talked about how they had discovered how certain molecules looked or felt referring to their presentation in the model. The quotations below provide examples of this:

"Yeah. I learned how the glucose felt. I didn't know actually know it was kind of like that." – Ariel

"because at first I didn't know what was sodium, potassium, kind of, what colours and things were." – Erika

These quotations show that these students had taken the representation of the molecules in the model as what the molecules look and feel like in reality. However, it is impossible to know what a molecule would feel like, and the colours used to represent the molecules were fictitious to differentiate them visually within the model. Although the model was designed to be as realistic as possible, some stylised representations were required for clarity, but it seems that some students were not able to differentiate these aspects as representative.

One misconception that was noted was an anthropomorphising of the cell, which has been shown to be a common misconception in cell biology (Dreyfus & Jungwirth, 1989; Flores et al., 2003) (Section 2.1.2 for more detail):

"I think, I think it did, um, like moving it through the, cos it shows that some particles don't belong outside the cell and some do. So you could say, you could say that sodium ions don't really want, I think, I think that's what I gathered that sodium ions don't want to, they don't really go outside the cell that much. They just want to like stay inside." – Lea

Although this was the only instance of an anthropomorphising misconception, it is a well-documented issue in cell biology and therefore relevant to mention.

An additional misconception found was that the membrane proteins were fixed in place in the membrane, which was mentioned in 6 items of data. In reality, the membrane proteins are more fluid within the membrane, but this did not seem to translate to the students. This is supported by the cell knowledge answer changes described in Section 4.2.7.2, where students were shown to not be clear on the fluidity of the membrane overall. It is possible that the membrane proteins in the model may have been more difficult to move, masking the fluidity of the membrane.

There were slightly more items of data in the ‘misconceptions’ theme from students in the non-haptic condition than haptic condition (19 items of data for non-haptic, and 11 for haptic), with the largest difference in that more non-haptic student pairs demonstrated the misconception that the membrane proteins were fixed (4 non-haptic, 1 haptic). It is possible that the haptic feedback may have allowed students to feel more movement of the membrane proteins as they manipulated them, whereas the non-haptic students would not have experienced that feedback and assumed that they were fixed or rigid. If so, this could be an example of the modality-appropriateness hypothesis (Welch & Warren, 1980) discussed in Section 2.4.5, which suggests that when presented with incongruent information from visual and other sensory information, the sense which allows the greatest precision would be favoured. However, a difference of three students between conditions demonstrating the fixed membrane protein misunderstanding is a small discrepancy, and therefore should be treated tentatively.

In summary there were some misconceptions found in the discussions with students on their learning with this activity, although those who expressed misconceptions were in the minority. It is possible that many would not reveal misconceptions without being probed and challenged, but the analysis of the true/false/unsure section of the cell knowledge test can explore potential misconceptions in more detail (Section 5.2.2.7). For those who did express misconceptions, the most common was believing that the colour and feel of the molecules was realistic and that the membrane proteins were fixed in place. With the commonality of a broad range of misunderstandings in cell biology in general (as discussed in Section 2.1.2), the misconceptions found in this data are not unexpected. However, as seen in the ‘increased understanding’ theme and the cell knowledge question answer changes in Section 4.2.7, other misconceptions were avoided or corrected by using and learning from the intervention. It may be that the misconceptions identified in this theme are especially liable to propagation whilst using VR environments capable of providing haptic feedback, and therefore specific care may have to be taken to mitigate them in future.

4.3.1.2.10 Summary and conclusion

In summary, five major themes and nine minor themes emerged from the data through thematic analysis of the interviews, which covered a broad range of elements concerning student experiences regarding their perceptions of the intervention and their learning. The ‘praise for the system’ and ‘liked features’ themes showed that the students generally enjoyed using the system and the ‘comparison with regular teaching’ showed a preference for interaction in their learning. The ‘learning’ theme supported the quantitative results (Section 4.2) by demonstrating increased understanding overall and the correction of certain misconceptions of the inner workings of the cell. The ‘learning’ theme highlighted how students felt that they would retain their increased knowledge, which was demonstrated by the quantitative results (Section4.2.5). Additionally, the most discussed topics in the ‘learning’ theme were the size and scale of molecules and the membrane channels. The ‘difficulties’ theme identified issues such as technological problems which may have interrupted students’ learning. However, the ‘easy’ theme showed evidence that despite the difficulties described by some students, most found the system easy to use and the completion of worksheets did not indicate a difficulty in finishing the activity (Appendix RR). The ‘distraction’ and ‘focus’ themes revealed that although some visual aspects could distract the pilot from the task, students felt more focused on the activity than they would be in normal lessons. The ‘misunderstanding’ theme identified certain misunderstandings about the cell from a minority of students, which corresponds with previous literature on misunderstandings and misconceptions in cell biology (Section 2.1). The ‘haptic’ theme suggested that those in the haptic condition were aware of haptic feedback providing information on the properties of molecules and components of the cell, and although some students discussed feeling forces across the cell membrane during diffusion, most in the haptic condition did not comment on feeling forces.

According to DCT (Section 2.3.3), the presence of haptic feedback would enable the use of the haptic processing channel, spreading the cognitive load of processing complex information (such as cell biology) and allowing for more efficient processing. The ‘haptic’ and ‘feeling forces’ themes showed that generally, students in the haptic condition detected the presence of haptic feedback. Discussions in the ‘collaboration’ theme suggested that discussion and communication between peers during the task was beneficial towards learning, potentially allowing the spreading of cognitive load between the working memories of learning pairs (Section 2.4.4.1.2). However, the results of the ANOVA (Section4.2.5) showed that the presence of haptic feedback had no significant effect on the increase of cell knowledge demonstrated by students after the activity. There are several potential reasons as to why haptics had no significant effect on learning gains in this study (which are discussed further in Section5.2.1.3), including a high amount of cognitive load experienced by the students, potential sources of which were identified in themes such as ‘difficulties’ and ‘novelty’.

Across the themes identified through the thematic analysis, it has been discussed that certain aspects of the system and activity may have added cognitive load to the students’ working memory. Although the use of the haptic processing channel for this information is thought to lower the overall cognitive load (Section 2.4.2.2), it has been suggested in the literature that if load is high enough then an additional modality may not be sufficient to stop the negative effects on learning (Sweller, 2011) (Section 2.4.4). The novelty of the system was a prominent topic in the interviews, which according to CLT (Sweller, 1994) has the potential to add extraneous load as the student learns to navigate and use the system to complete the task whilst simultaneously learning complex scientific concepts. Some students described difficulties with grasping particles, potentially demonstrating the added difficulty in using a novel system in this study. A smaller number of students commented on the difficulty of the task (discussed in 12 interviews), which also has the potential to increase cognitive load. However, the completion of worksheets (Appendix RR) suggest that the task was not so difficult that it affected the students' ability to complete the activity, and it was discussed that the 'task difficulty' theme may be evidence that the task was challenging enough for the beneficial effects of collaborative learning to take effect (Section 2.4.4.1.2). Themes regarding visual aspects of the system suggest that visual features were prominent and appreciated by students. Additionally, the 'seeing' and 'visualisation' themes showed that non-haptic students discussed visual aspects more than those in the haptic condition. It was discussed that, as the haptic condition had more information to process, it is possible that increased cognitive load of processing haptic feedback may have lowered their attention to the visual aspects of the system compared to those in the non-haptic condition. In the 'haptics' theme, it was shown that most students in the haptic condition did not discuss the forces across the concentration gradient. It was discussed that highly stimulating visuals, high intrinsic load from the complex biological concept of diffusion and high extraneous load from a novel system with interacting elements may have the potential to overload a pilot's working memory, dampening the presence of the haptic information across the membrane.

It is possible, therefore, that despite the presence of haptic feedback making use of a haptic processing channel, the increased cognitive load (intrinsic, germane, and extraneous) placed upon the students' working memory may have made the beneficial effects of using an additional modality unfruitful. The opinions of the students gathered through the interviews here has provided an insight into their experience and revealed that many students experienced factors during their learning which are known to increase cognitive load, possibly providing an explanation or insight into the non-significant results found in the quantitative analysis.

5 Discussion

5.1 Introduction

This chapter presents a discussion on the findings from the main study described in Section 3.4, the results of which were presented in Chapter 4. This chapter will refer to the following research questions (shown previously in Section 3.2):

1. Will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?
2. Does existing spatial ability have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?
3. Does existing fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?
4. What design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools??

This chapter discusses how the study findings answer the research questions and contribute to the gaps in knowledge concerning the use of haptic feedback in science education, which they aim to address.

RQ1, RQ2 and RQ3 were answered using quantitative data from the tests of cell knowledge, spatial ability and fine dexterity (Section 4.2), and RQ4 was explored using the thematic analysis of the interview transcripts (Section 4.3). In this chapter, I discuss and interpret these findings, referring to the relevant theoretical foundations and previous studies discussed in the literature review (Chapter 2). This chapter also concludes the thesis by identifying contributions to knowledge, and discussing implications, limitations, and recommendations.

5.2 Quantitative analysis discussion

This section will discuss the findings from the quantitative analyses for the main study described in Section 3.4, the results of which were presented in Chapter 4. This included analysis using a mixed ANOVA (Section4.2.5), mixed ANCOVAs (Section 4.2.6) and the changes in answers for the true/false/unsure section of the cell knowledge test from pre to post-intervention (Section 4.2.7). The findings from these analyses will be discussed in turn, as well as their meaning in the context of the research questions.

5.2.1 RQ1

1. Will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?

As discussed previously (Section 3.4.1), to answer RQ1, two experimental conditions were used in the main study: haptic and non-haptic. The haptic condition allowed users to feel all touch feedback from the model, including drag force and concentration gradients. The non-haptic condition was identical to the haptic condition, but with all haptic force feedback form the model removed. Learning was measured using an identical pre and post-intervention test of cell knowledge.

To compare the learning of the haptic and non-haptic groups, a 2x3 mixed ANOVA was conducted which also showed that there was no effect of condition on the differences of knowledge scores across the pre-intervention, post-intervention, and retention-tests.

Therefore, whether the participants were in the haptic or non-haptic condition did not affect the change in scores over time. To answer RQ1, a haptic environment was not shown to enhance learning of complex cellular concepts compared to a non-haptic method in this study.

The literature discussed in Chapter 2 suggested that the use of haptics whilst learning complex scientific topics may be beneficial. DCT (Paivio, 1969), CLT (Sweller, 1994) and Embodied Cognition (Section 2.4.2.1) were discussed in Sections 2.3.3, 2.4.2.2 and 2.4.2.1 as theoretical justification for the use of haptics in the learning of complex cellular biological concepts. The following section (5.2.1.1) will discuss the results of RQ1 in relation to these theories.

5.2.1.1 Results of RQ1 in relation to Additional Sensory Channel and Embodied Cognition theories

Cell biology and diffusion were chosen as topics for this project as they are known to be particularly difficult to understand due to their abstract nature, with misconceptions common at all levels of education (discussed in Section 2.1) (Dreyfus & Jungwirth, 1989; Flores et al., 2003). Learning these topics requires the processing of abstract and cognitively demanding information, and therefore methods of lowering the cognitive demand of learning these topics are thought to be beneficial.

As discussed in Section 2.3.3, DCT (Paivio, 1969) supports the use of multiple modalities in learning using the ‘modality principle’ (Millar, 1999), which assumes that every modality has its own processing channel within working memory. Also utilising the modality principle, CLT (Sweller, 1994) suggests that whilst learning, an individual’s working memory is put under cognitive load as new information is processed, and that by utilising several channels, cognitive load can be split between them in order to be decreased and therefore facilitate learning. Together DCT (Paivio, 1969) and CLT

(Sweller, 1994) have been referred to as The Additional Sensory Channel theory (Zacharia, 2015), which suggests that by using haptic feedback, cognitive load from complex cellular information can be alleviated from students' working memories using the haptic modality processing channel, allowing for more efficient information processing. Evidence discussed in Section 2.4.3 however, showed that research on the effectiveness of using haptics in science education is mixed, but suggests that haptics may be particularly useful for the learning of abstract concepts where visual information is inadequate (Minogue & Jones, 2006; Zacharia, 2015). Cell biology is known to contain abstract concepts (Section 2.1.2) including the effect of the concentration gradient across the cell membrane, which is a concept which is not adequately described with visual information alone. Therefore, the literature would suggest that the topic chosen for the VR activity in the main study would be especially suited to the use of haptics to benefit learning. Overall, the Additional Sensory Channel theory (Zacharia, 2015) suggests that for the topic of cell biology, the use of an additional haptic processing channel may benefit the learning of complex concepts by lowering the cognitive load on students' working memories.

However, the ANOVA and ANCOVA detailed in Sections 4.2.5 and 4.2.6 showed that in this study, there were no significant differences between haptic and non-haptic conditions in learning gains, contrary to what the literature would suggest. There is literature suggesting that certain factors may have the ability to diminish the beneficial effects of an additional haptic channel whilst learning complex concepts. These factors include excessive cognitive load and the effects of visual dominance, which are discussed further in Sections 5.2.1.3 and 5.3.1.

An additional theory that suggested haptic feedback could be beneficial in learning complex information was Embodied Cognition (Barsalou, 2008) (Section 2.4.2.1), which suggests that understanding is constructed by information represented within the sensory and motor systems, and stresses the importance of constructing multimodal representations (Barsalou, 2008). As discussed in Section 2.4.2.1, Embodied Cognition (Barsalou, 2008) suggests that touch feedback can be used as a cognitive anchor for understanding abstract concepts, building schemata of haptic information grounded in the haptic sense, which cannot be recreated by other sensory modalities (Reiner, 2009). These haptic schemas could lead to the construction of conceptual metaphors which learners can use to develop a deeper understanding of, or to ground scientific concepts (Zacharia, 2015). The literature discussed in Section 2.4.2.1.4 also suggests that the potential for creating embodied experiences is more important in learning than physicality (Han, 2013; Zacharia & Olympiou, 2011). Therefore, according to Embodied Cognition (Barsalou, 2008), manipulation without haptic feedback (as in the non-haptic condition of this study) may be able to create embodied experiences due to the inherent physicality of the activity. However, the addition of haptic feedback would provide additional, unique perceptual experiences in which to ground abstract concepts such as those in cell biology. Embodied Cognition (Barsalou, 2008) would suggest therefore, that the haptic condition in this study would result in more embodied experiences, more complete multisensory representations, and therefore a better understanding of the biological concepts represented in the learning activity.

The results of the ANOVA and ANCOVA (Sections 4.2.5 and 4.2.6) are also contrary to what Embodied Cognition (Barsalou, 2008) would suggest. The literature suggested that it is the ability to create embodied experiences which makes virtual manipulatives beneficial for learning (Section 2.4.2.1.4), and therefore according to Embodied Cognition (Barsalou, 2008), the findings for RQ1 may suggest that although the non-haptic condition may have provided limited embodied experiences due to the process of physical manipulation in virtual reality, adding haptic feedback did not increase the number of embodied experiences sufficiently to affect the results. As discussed in Section 4.3.1.1.1.1, diffusion and concentration gradients across the membrane are concepts which are especially difficult to understand with visual information alone, however the 'haptics' theme identified in the thematic analysis (Section 4.3.1.1.1) suggests that students in the haptic condition may not have perceived the haptic feedback regarding the concentration gradient as intended. If students did not perceive the haptic feedback for this topic (which the literature suggests haptic information should be particularly useful for), it is therefore possible that the differences in embodied experiences between the haptic and non-haptic conditions were not substantial enough to significantly affect the results.

5.2.1.2 Results of RQ1 in relation to previous research

As discussed in Section 2.4.3, the literature showed that the evidence for the effectiveness of haptics in science education is mixed. Of studies that compared haptic and non-haptic conditions in learning science, five studies were contrary to the findings of this project and found that haptic information was beneficial to the learning of the participants (Bivall et al., 2011; Brooks et al., 1990; Hallman et al., 2009; Jones, Minogue, Tretter, et al., 2006; Minogue & Jones, 2009). However, six studies found no benefit of haptic feedback, as found in this study (Bivall et al., 2007; Jones et al., 2003; Jones, Minogue, Oppewal, et al., 2006; C. H. Park & Howard, 2014; Wiebe et al., 2009; Young et al., 2011). There are a few explanations for why the resuts of this study may have corroborated or not corroborated the findings of previous research, which will be discussed in this section.

Although previous studies involved topics in science education, most were not focused on cell biology as this study was. As discussed in Section 2.1, cell biology has been shown to be an especially difficult topic due to it’s complex, abstract nature, and was therefore chosen as the learning topic in this study. Previous studies have found mixed results on the effects of haptic feedback on learning in varied topics in science, including cell membranes (Jones, Minogue, Oppewal, et al., 2006; Minogue & Jones, 2009), gears (Hallman et al., 2009), magnetic fields (Brooks et al., 1990), bio-molecuar binding (Bivall et al., 2011; Bivall et al., 2007), viruses (Jones et al., 2003; Jones, Minogue, Tretter, et al., 2006), point charges (J. Park et al., 2010), levers (Wiebe et al., 2009) and bouyancy (Young et al., 2011). All these scientific topics involve abstract forces where visual informaion may not be sufficient to increase understanding and is therefore suitable for the use of haptics. Yet, mixed results from these studies make it difficult to draw conclusions on the effect of haptics on learning (Zacharia, 2015). It may be possible that different scientific concepts require differing demands for visualisation, which therefore affects the cognitive load placed upon the learner. Should the cognitive demands on the learner differ between domains, this could affect the consistency in findings for the effectiveness of hapitcs in learning complex concepts in science.

However, there have also been mixed results of the effects of haptics within the topic of cell membranes. As discussed in Section 2.4.3, Jones, Minogue, Oppewal, et al. (2006) found in their study that although students found haptic feedback engaging, no cognitive benefits were found. The authors suggested that the scoring rubrics used in their study may not have adequately represented subtle changes in understanding. In a later study, Minogue and Jones (2009) explored the effects of haptics on learning in the same topic, but with an improved test of knowledge. The authors found that students receiving haptic feedback were more likely to reach higher levels of sophistication in their understandings than those who received visual information only. The researchers of these two studies therefore found mixed results for the effect of haptics on learning within the topic of cell membranes, attributing their more positive results to improved measurement of learning gains. The test of knowledge used in this study was designed by biologists and biology educators to correspond to students' abilities and curriculums, and to include a mixture of question formats to provide an accurate representation of students' knowledge (Section 3.4.4). As in Jones, Minogue, Oppewal, et al. (2006), it is possible that the test of cell knowledge in this study may not been precise enough to measure subtle differences in learning. However, evidence from the thematic analysis discussed in Section 4.3.1 provided additional insight into students' learning and found no notable differences in increased understanding between haptic and non-haptic students (percieved or demonstrated) (Section 4.3.1.1.3.2). The findings from the thematic analysis therefore correspond with the quantitative results, supporting the validity of the test of cell knowledge used in this study.

In addition to suggesting that their scoring rubrics may not have been adequate, Jones, Minogue, Oppewal, et al. (2006) also suggested that high cognitive load and visual dominance effects during the task may have affected the ability of haptics to benefit learning. Wiebe et al. (2009) also suggested that cognitive load from using new techology to incorporate and coordinate haptic feedback may have had a negative affect on learning in their study. As discussed in Section 2.4.4, CLT (Sweller, 1994) suggests that abstract, difficult concepts and novel presentation of information with interacting elements can increase cognitive load on the working memory, which if in excess could affect the ability of students to process information. Additionally, as discussed in Section 2.4.5, visual dominance describes how the visual sense can dominate other senses, potentially affecting the attention afforded to haptic feedback during learning activities. Consistent with the conclusions of Jones, Minogue, Oppewal, et al. (2006) and Wiebe et al. (2009), the thematic analysis in this study found evidence of potential sources of excess cognitive load and effects of visual dominance. These factors will be discussed further in Section 5.2.1.3.

In contrast to this project, Mingue and Jones (2009) used a Phantom Touch 3D stylus-based device (Figure 10) and did not use collaboration between students during their learning activity. Although the multi-fingered haptic device used in this study was designed to be more intuitive than the Phantom Touch 3D device used in Pilots 1, 2 and 3 (Section 3.3.4), there were reported technical difficulties for some students, which may have made navigation difficult (Section 4.3.1.1.5). Additionally, the model used in this project was visually more complex than that of Mingue and Jones (2009), potentially contributing addtional cognitive load to the task. Additionally, although collaboration is thought to be beneficial for complex tasks, ‘transaction costs’ have the potential to nullify the effect of collaboration on lowering strain on working memory (Section 2.4.4.1.2). It is possible that the use of collaboration may have added cognitive load to the task in this study, however, the 'collaboration' theme identfiied in the thematic analysis suggests that collaboration was a positive feature. Students reported enjoying the collaborative aspect of the task and stated that it was preferable to working alone (Section 4.3.1.1.2), suggesting that transaction costs were not an issue for these students.

This section discussed the findings of RQ1 in relation to previous studies in the research topic. It was discussed that literature on the effect of haptics in learning science is mixed, and therefore the findings of this study were consistent with some studies (Bivall et al., 2011; Brooks et al., 1990; Hallman et al., 2009; Jones, Minogue, Tretter, et al., 2006; Minogue & Jones, 2009), and and inconcsistent with others (Bivall et al., 2007; Jones et al., 2003; Jones, Minogue, Oppewal, et al., 2006; C. H. Park & Howard, 2014; Wiebe et al., 2009; Young et al., 2011). The incongruency of the findings of this study with previous studies showing beneficial effects of haptics may be influenced by differences in learning topic and method of haptic interaction, which may have affected the cognitive load expereinced by learners. Potential explanations as to why haptic feedback was found to provide no benefit for learning in this study, including excess cogntitive load and visual dominance, are discussed further in the following section (5.2.1.3).

5.2.1.3 Theoretical explanations for the findings of RQ1

There are two main theories that may explain why haptic feedback did not benefit learning in this study: excess cognitive load, and visual dominance.

5.2.1.3.1 Excess cognitive load

As discussed in the literature review (Section 2.4.2.2), cognitive load is separated into three elements: intrinsic, extraneous and germane (Sweller, 2011). Intrinsic cognitive load occurs from the information being learned and extraneous cognitive load occurs by how information is presented. Germane cognitive load refers to the cognitive resources used in constructing schemas and processing information to long term memory. Intrinsic, extraneous, and germane load are additive, meaning that they all contribute to the cognitive load that is imposed on working memory. Therefore, an excess of cognitive load has the potential to overload the working memory and negatively impact learning (Sweller, 2011). It has been suggested that that adding complex information from an additional modality and using instructional programs involving combinations of unfamiliar elements have the potential to overload the working memory, negating the effects of using multiple modalities to more effectively process information (P. A. Kirschner, 2002; Sweller, 2011).

As discussed in the literature review (Section 2.4.4) and in Section 5.2.1.2, cognitive overload of the working memory has been implicated by other researchers as a possible reason as to why haptics did not benefit learning in their studies (Minogue et al., 2006; Wiebe et al., 2009). Additionally, although the learning environment was designed in this study to be as intuitive as possible (Section 3.3), it is possible that extraneous cognitive load may have affected the ability of haptic feedback to benefit the processing of information. Qualitative data from interviews regarding the student's perspectives on the system can provide some insight into the cognitive load they may have experienced, which is discussed further in Section 5.3.

5.2.1.3.2 Visual dominance

As discussed in Section 2.4.5, the visual sense has been shown in many studies to dominate other senses. To review, there is evidence that when presented with multiple modalities, attention is often afforded to the visual sense: an effect called 'visual dominance' (Posner et al., 1976). Two prominent theories on visual dominance are the 'modality-appropriateness hypothesis' (Welch & Warren, 1980) and the 'directed-attention hypothesis' (Posner et al., 1976). The modality-appropriateness hypothesis (Welch & Warren, 1980) suggests that when presented with incongruent information from visual and other sensory information, the sense which allows the greatest precision would be favoured. This suggests that visual information is favoured because it is usually the most appropriate for the task (Pye, 2008). However, for information where haptics may provide more accurate information over visual, this hypothesis suggests that haptics would be preferred. Furthermore, Klatzky et al. (1991) suggested that, in circumstances when visual information is adequate for the task at hand, attention may not be attuned to haptic exploration due to its high processing cost relative to its benefits. The directed-attention hypothesis (Posner et al., 1976) suggests that when attention is concentrated toward any one modality, a reduction in the availability of attention towards input from other modalities occurs. This hypothesis therefore suggests that if attention is directed to visual information, there may be decreased attention for less-attended sensory modalities such as touch.

For learning about the concentration gradient in the task for this study, haptic feedback would have provided the most precise information, as this concept is difficult to convey with visual-only methods. Therefore, according to the modality-appropriateness hypothesis (Welch & Warren, 1980), attention should have been directed towards the haptic sense. However, for tasks early in the activity (grasping/moving/adding or removing molecules), visual information was likely the most suitable for the students' needs, and therefore may have been the focus of attention according to this hypothesis. Additionally, students were exposed to visual information first, potentially creating a bias towards the visual sense according to the directed-attention hypothesis (Posner et al., 1976). It is possible therefore, that being primed with visual information coupled with a high amount of cognitive load from the learning content and presentation of information, meant the students' attention may not have been properly attuned to the haptic feedback provided. Qualitative data from the interviews provide some insight into the impact of the visual and haptic feedback on the students and is discussed further in relation to visual dominance in Sections 4.3.1.1.1.1,5.4.1.1.1 and 5.4.1.1.3.

In summary, the ANOVA answered RQ1 by showing that there were no significant differences in learning gains between the haptic and non-haptic conditions in this study. The literature points to some explanations as to why this may have been the case, including the effect of excess cognitive load on the working memory's ability to process information and the effects of visual dominance (discussed further in Section5.3.1.1 and 5.3.1.3).

5.2.2 True/false/unsure section analysis discussion

This section will discuss the analysis of the true/false/unsure section of the cell knowledge test shown in Section 4.2.7. This section will begin by recapping the quantitative analyses and the context of the true/false/unsure section analysis within analysis of the data overall. The findings of the true/false/unsure analysis will be discussed, including the evidence found for existing misconceptions in the sample, increased learning, misconceptions challenged by the intervention, misconceptions that may have been introduced during the activity, and differences between haptic and non-haptic conditions. Finally, a conclusion will discuss the findings and their relation to findings from the ANOVA and thematic analysis.

5.2.2.1 Analysis review

To provide context for this section, the true/false/unsure data and analysis will be reviewed here. During data collection, participants were separated into two conditions for the intervention: haptic and non-haptic. The intervention involved using the VR learning environment to interact with a cell membrane model and complete an activity worksheet (Appendix DD). Students in the haptic condition experienced the activity with the addition of haptic feedback from the model, whilst the non-haptic condition completed the same activity with haptic feedback removed. All students completed a test of cell knowledge both pre and post-intervention, which as discussed in Section 3.4.4, included 3 sections: 1) a section for students to write statements about the cell membrane with a confidence indicator, 2) a short answer question and 3) a section with several statements about the cell membrane where students chose whether the statements were true, false, or whether they were unsure. The overall scores of the cell knowledge tests were used to calculate the ANOVA (Section4.2.5), which tested the significance of the difference between pre and post-intervention scores, and whether the difference was affected by condition (haptic or non-haptic). The results of the ANOVA showed that overall, the students scored significantly higher after the intervention than before, but there was no significant difference between the haptic and non-haptic conditions.

5.2.2.2 Purpose of the true/false/unsure section analysis

Although the ANOVA showed that students' knowledge improved overall after the intervention, it could not provide more detail on which concepts may have been affected by the intervention and to what extent. Analysis of the true/false/unsure section of the cell knowledge test allowed a more detailed discussion of how students' knowledge changed from pre to post-intervention. Each statement corresponded with the understanding of certain concepts regarding the cell membrane (Table 40), and therefore an analysis of how students answered each statement both pre and post-intervention was conducted to gain insight into the learning of those concepts.

The analysis of the true/false/unsure section of the cell knowledge test serves multiple purposes for this study. These are as follows:

1. To determine that the students in this sample held misconceptions on the topic of cell biology, as predicted by the literature, and whether their misconceptions matched those described in the literature.

As discussed in Section 2.1, the literature showed that cell biology is a difficult topic with misconceptions common from primary to post-graduate levels of education (Dreyfus & Jungwirth, 1989; Flores et al., 2003). The literature would therefore suggest that a typical sample of students would also hold misconceptions on the topic of cell biology. As each statement in the true/false/unsure section corresponded with the understanding of certain concepts regarding the cell membrane, an analysis of the answers from the pre-intervention test was able to identify whether students showed existing misconceptions. Testing for existing misconceptions assured that the students in this study were typical according to the literature, and that the intervention would not have been superfluous. Existing misconceptions shown in the sample and a comparison with misconceptions shown to be common in the literature is discussed in Section 5.2.2.3.

2. To identify misconceptions that may have been challenged, not challenged, or introduced to the students by the intervention.

The change in answers from pre to post-intervention for the true/false/unsure statements were analysed to reveal patterns which could determine whether misconceptions were challenged, not challenged, or introduced to the students by the intervention. For example, should students answer incorrectly pre-test but correctly post-test, it would suggest that a misconception was challenged for those students by the intervention. Additionally, if students answered correctly pre-intervention but incorrectly at post-intervention, that would suggest that a misconception may have been introduced. Similarly, if many students answered incorrectly both pre and post-intervention, that would suggest that a misconception in that topic was not successfully challenged. An analysis of the answers pre and post-intervention for the true/false/unsure statements therefore, was able to add detail to the quantitative analysis by identifying which topics were addressed by the intervention.

3. To determine any differences between haptic and non-haptic conditions on whether misconceptions were challenged, not challenged, or introduced during the intervention.

As students were separated into haptic and non-haptic conditions for this study, differences between these groups in their answer changes for each statement from pre to post-intervention were identified and will be discussed. Possible reasons for differences or lack of differences between conditions are also discussed (Section 5.2.2.8).

4. To corroborate with the ANOVA and thematic analysis to create a more complete picture of the students' increased learning overall after the intervention.

Identifying patterns of increased learning and where misconceptions may have been challenged or not challenged, contributes detail to the findings of the ANOVA and thematic analysis (Section 5.2.2.5). The ANOVA showed that students demonstrated increased learning after the intervention, but it could not provide more detail on which concepts may have been affected by the intervention and to what extent. Additionally, the thematic analysis identified a theme of 'increased understanding' where students discussed perceiving increased understanding on certain topics. Topics identified in the true/false/unsure section analysis for which students showed increased understanding were compared to those identified in the 'increased understanding' theme.

5.2.2.3 Evidence of existing misconceptions

The analysis of the true/false/unsure section of the pre-intervention tests identified existing misconceptions held by the sample. These were identified by large proportions of students answering statements incorrectly, demonstrating misconceptions in the concept for which those statements corresponded. Table 40 shows each statement from the true/false/unsure section, corresponding concepts and the percentage/number of students who answered incorrectly pre-intervention.

Table 40: Percentage of students answering incorrectly by statement

Statement	Concept	% Answered incorrectly
1: The cell membrane is a barrier that stops everything from entering /leaving the cell.	Selective permeability of the membrane.	53% (34/64)
2: The cell membrane is fluid.	Fluidity of membrane.	61% (39/64)
3: The cell membrane contains membrane proteins that sit in a fixed position in the membrane.	Membrane proteins and their movement in the fluid cell membrane.	50% (32/64)
4: All membrane proteins form channels that allow anything to cross the membrane and enter the cell.	Channels/diffusion.	33% (21/64)
5: Oxygen can freely enter and exit a cell (does not need a channel).	Free movement of oxygen across cell membrane.	23.4% (15/64)
6: Glucose can freely enter and exit a cell (does not need a channel).	Selective permeability of membrane/glucose transport.	21.9% (14/64)
7: Carbon dioxide can freely enter and exit a cell (does not need a channel).	Free movement of CO2 across cell membrane.	35.9% (24/64)
8: Sodium can freely enter and exit a cell (does not need a channel).	Selective permeability of cell membrane and/sodium transport.	4.7% (3/64)
9: An oxygen molecule is smaller than a glucose molecule.	Relative sizes of molecules.	7.8% (5/64)

10: The cell membrane contains about 5 glucose channels.	Nature of the model in relation to the cell membrane.	17.2% (11/64)
11: If there is an equal amount of oxygen inside and outside the cell it will be harder for oxygen to enter than if there is more oxygen outside.	The passive diffusion of oxygen down a concentration gradient.	20.4% (13/64)
12: If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside.	The passive diffusion of carbon dioxide down a concentration gradient.	36% (23/64)
13: During aerobic respiration, a cell uses oxygen and glucose.	Aerobic respiration.	14.1% (9/64)
14: During aerobic respiration, a cell produces oxygen and water.	Aerobic respiration.	21.9% (14/64)

As shown in Table 40, the percentage of incorrect answers for each statement pre-intervention range from 4.7% to 61%, suggesting that pre-intervention, students held varying levels of misconceptions on biological concepts regarding the cell membrane. Some statements had a low percentage of incorrect answers suggesting that generally, students demonstrated few misconceptions on those topics. For example, Statement 8, which concerns the movement of sodium across the membrane, had only 4.7% of students answering incorrectly pre-intervention. Additionally, Statement 9, which concerns the relative size of oxygen and glucose, had only 7.8% of students answer incorrectly.

However, there were statements for which 50% or more of the students answered incorrectly pre-intervention. Statement 1 (the cell membrane is a barrier that stops everything from entering /leaving the cell) concerned the selective permeability of the membrane, where 53% of students answered incorrectly pre-intervention. Over half of students answered that the membrane stopped everything from entering/leaving the cell, suggesting a misconception on the permeability of the membrane. Statement 2 (the cell membrane is fluid) concerning the fluidity of the cell membrane had 61% of students answer incorrectly, suggesting a largely held misconception pre-intervention of the rigidity of the cell membrane. Statement 3 (the cell membrane contains membrane proteins that sit in a fixed position in the membrane) concerned the fluid movement of membrane proteins in the membrane, where 50% of students answered incorrectly pre-intervention, suggesting a misconception of rigidly positioned membrane proteins present in half of the sample.

Other statements had a lower, but notable percentage of incorrect answers pre-intervention. Statement 4 concerned channels/diffusion, where 33% of students answered incorrectly pre-intervention. Statement 5 concerned free movement of oxygen across cell membrane, where 23% answered incorrectly, and Statement 6 concerned the selective permeability of membrane/glucose transport, with 22% answering incorrectly. Statement 7 concerned free movement of CO_2 across the cell membrane, with 38% of students answering incorrectly. Statement 12, regarding the passive diffusion of carbon dioxide down a concentration gradient, found that 36% answered incorrectly. These percentages suggest that large portions of the sample held misconceptions pre-intervention regarding concepts including channels, diffusion, the free movement of particles through the membrane and passive diffusion of particles along a concentration gradient.

Existing misconceptions identified in the sample include concepts that have been identified in the literature as common sources of misconnections within cell biology. The selectivity of the cell membrane (as represented by Statement 6) was a topic of many erroneous explanations by students identified in Dreyfus and Jungwirth (1989). The concept of the membrane as a static rather than a fluid system was also identified as a common misconception by Storey (1990), which corresponds to the misconceptions identified from Statements 2 (the cell membrane is fluid) and 3 (the cell membrane contains membrane proteins that sit in a fixed position in the membrane).

As discussed in Section 2.1.2.1.2, the concept of randomness (including diffusion) was also identified in the literature as a common source of misconceptions (Friedler et al., 1987; Garvin-Doxas & Klymkowsky, 2008; Lander, 2007; Malinska et al., 2016; Odom, 1995; Sanger et al., 2001). Statements 5, 6, 7 and 12 concerned the diffusion of molecules through the membrane for which a range of 22-38% of students answered incorrectly. These percentages suggest that misconceptions on the topic of diffusion across the membrane existed in a sizable portion of the sample, as the literature would suggest.

In summary, corresponding with the literature, existing misconceptions were identified in the sample through the analysis of the true/false/unsure section of the cell knowledge tests completed before the intervention. These misconceptions concerned concepts including the selective permeability and fluidity of the cell membrane, glucose transport, fluidity of the movement of membrane proteins and passive diffusion of molecules through the membrane. These parallel the literature, which identified selective permeability, fluidity of the membrane and diffusion as sources of common misconceptions. These findings show that the sample used in this project were found to have existing misconceptions on the topic of cell biology as predicted by the literature, and therefore the sample was suitable for the use of a haptic intervention in this study.

5.2.2.4 Selection of relevant statements

After confirming that the students held existing misconceptions in the topic of cell biology, the analysis continued to use changes in answers for each statement from pre to post-intervention to determine evidence of the challenging of, failure to challenge, or the introduction of misconceptions due to the intervention.

The analysis was used to identify salient statements where evidence of challenging, not challenging or introducing misconceptions was found. A summary of the statements that were found to be relevant is shown in Table 41. Table 41 also includes the concept each statement refers to, the main changes pre to post-intervention across the sample and a summary of the possible explanation for those findings. An extended version of Table 41 which includes every statement from the true/false/unsure section of the knowledge test is shown in Appendix SS, but the version shown here includes statements for which the findings of the pre to post-intervention answer changes were particularly relevant or interesting. Relevant statements were chosen if the answer changes from pre to post-intervention showed a pattern of change including moving from correct to incorrect or unsure answers, or from incorrect to correct or unsure answers. These patterns may indicate a general change in knowledge for certain concepts and were therefore chosen to discuss further.

Table 41: Summary of True/False/Unsure cell knowledge test answers from pre to post-intervention and results

Statement	Concept	Changes pre to post-intervention	Interpretation of findings
2: The cell membrane is fluid	Fluidity of membrane	Majority answered incorrectly both pre and post-intervention (46%).	Misconception was not challenged. This was expected however, as the fluidity of the membrane was not programmed into the model (Section 3.4.2).
3: The cell membrane contains membrane proteins that sit in a fixed position in the membrane	Membrane proteins and their movement in the fluid cell membrane.	Most answered incorrectly both pre and post-intervention (39%). Second most frequently, participants changed from being unsure to being incorrect post-intervention (25%).	Many already held a misconception that proteins are fixed in place. A misconception may have been introduced to those who answered unsure and changed to incorrect.
5: Oxygen can freely enter and exit a cell (does not need a channel)	Free movement of oxygen across cell membrane.	Most frequently, answers were correct both pre and post-intervention (46%). Second most frequent change was from unsure to correct (28%). Third most frequent change was incorrect to correct (23%).	Most understood the topic before the intervention. For those who did not, most changed to a correct answer after the intervention.

6: Glucose can freely enter and exit a cell (does not need a channel)	Selective permeability of membrane/glucose transport.	Most frequent was unsure to correct (37%). This was followed by answering correctly both pre and post-intervention (30%).	Some understanding already, but most of those who did not answer correctly pre-intervention showed learning by answering correctly post-intervention.
7: Carbon dioxide can freely enter and exit a cell (does not need a channel)	Free movement of CO_2 across cell membrane.	Most frequent answer change unsure to correct (39%). The second most frequent answer change was from incorrect to correct (36%).	Most students demonstrated learning or challenging of misconceptions for this statement.
10: The cell membrane contains about 5 glucose channels	Nature of the model in relation to the cell membrane.	Most frequent response was unsure at pre and post-intervention (36%). Second most frequent was unsure to correct (19%). Little variation in frequency between other remaining answer change categories.	Included to test whether students understood that the model was a small part of the membrane overall. Some students were knowledgeable pre-intervention, and there was evidence of increased learning for some. Little variety in remaining answer change categories indicates confusion on this topic.

11: If there is an equal amount of oxygen inside and outside the cell it will be harder for oxygen to enter than if there is more oxygen outside	The passive diffusion of oxygen down a concentration gradient	Most frequent category correct both pre and post-intervention (28%), followed by unsure to correct (14%). Little variation in frequency between other remaining answer change categories.	A small percentage were able to answer correctly pre and post-intervention, and evidence of increased learning for some. Little variation between other answer change categories indicates confusion on this topic.
12: If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside	The passive diffusion of carbon dioxide down a concentration gradient.	Most frequently, students answered unsure pre and post-intervention (20%). Following this was changing from incorrect to correct (18%).	Students more unsure about passive diffusion down a concentration gradient for CO^2 than O^2. Little variation between other answer change categories indicates confusion on this topic. It is possible that students were confused by the question resulting in unsure answers pre and post-intervention. Confusion on this topic suggests that as with O^2, passive diffusion along concentration gradients could be a useful topic in further research.

5.2.2.5 Evidence of increased learning and challenging existing misconceptions

As discussed in Section4.2.5, the ANOVA showed that overall, students demonstrated significantly increased understanding after the intervention, as measured by the pre and post-intervention knowledge tests. The true/false/unsure question analysis provided insight into which concepts students showed increased understanding in by analysing the pre and post-test answers for each statement. Statements where students frequently changed from an unsure or incorrect answer pre-intervention to a correct answer post-intervention would suggest increased understanding. Furthermore, statements where students frequently changed from an incorrect answer pre-intervention to a correct answer post-intervention would suggest the challenging of an existing misconception. This section will discuss statements which suggest these changes in knowledge, and in the case of increased knowledge, whether the finding is corroborated by the thematic analysis.

5.2.2.5.1 Statement 5: Oxygen can freely enter and exit a cell (does not need a channel)

Statement 5 refers to the free movement of oxygen across the cell membrane, and the changes in answers from pre to post-intervention would suggest there was increased learning in this concept for some students. The most frequent answer category was answering correctly both pre and post-intervention (46%; 31 students), but the second most frequent category was from an unsure answer to a correct answer post-intervention (28%; 18 students), and the third most frequent was from an incorrect answer to a correct answer (23%; 15 students). Therefore, 51% of students (33) changed from being either unsure or incorrect pre-intervention to answering correctly post-intervention. This would suggest that although some students had existing knowledge of the free movement of oxygen through the membrane, half of the students increased their understanding on this concept. As discussed in Section 4.3.1.1.3.2, the thematic analysis identified ‘increased understanding’ as a theme, suggesting that a notable number of students perceived an increase in understanding from the intervention, corroborating the results of the ANOVA. Free movement of oxygen was a topic mentioned multiple times in the interviews, with 13 items of data concerning this topic coded to the 'increased understanding' theme. The analysis of the true/false/unsure questions therefore supports the findings from the thematic analysis, suggesting that students both perceived and demonstrated learning in the topic of the free movement of oxygen through the membrane. Additionally, 23% of students changed from an incorrect answer pre-intervention to a correct answer post-intervention, which suggests that over a fifth of the students had their existing misconception successfully challenged by participating in the intervention activity.

Comparing the results by condition, although more non-haptic students changed from an incorrect answer to a correct answer (3 haptic, 12 non-haptic), and more non-haptic students changed from unsure to correct (6 haptic, 12 non-haptic), this was due to the proportion of students from each condition who answered incorrect or unsure pre-intervention, therefore, no differences between the conditions could be concluded.

5.2.2.5.2 Statement 6: Glucose can freely enter and exit a cell (does not need a channel)

Statement 6 concerned the selective permeability of the membrane and glucose transport. The most frequent change in answers for this statement was from unsure pre-intervention to correct post-intervention (38%; 24 students), the second most frequent category was correct both pre and post-intervention (31%; 2 students), and the third was changing from incorrect to correct (17%; 11 students). Therefore, 54% of students changed from answering either incorrectly or as unsure pre-intervention to answering correctly post-intervention, indicating an increased understanding in this topic. These findings are supported by the thematic analysis, which showed that the movement of glucose across the membrane via channels was a topic included in the 'increased understanding' theme (Section 4.3.1.1.3.2). This suggests that students both perceived (as shown by the thematic analysis) and demonstrated (as shown by the cell knowledge test) learning in the topic of selective permeability of the membrane and glucose transport. Additionally, 17% (11 students) changed from an incorrect answer pre-intervention to a correct answer post-intervention, indicating that for some students, existing misconceptions were challenged by participating in the intervention.

Comparing the answer changes by condition for this statement, more haptic students changed from correct to incorrect (3 haptic, 0 non-haptic) and more non-haptic students changed from unsure to correct (15 non-haptic, 9 haptic). However, these changes can be explained by the proportion of haptic and non-haptic students who answered correctly or as unsure pre-intervention, therefore, no significant differences between condition were determined.

5.2.2.5.3 Statement 7: Carbon dioxide can freely enter and exit a cell (does not need a channel)

Statement 7 concerned the free movement of carbon dioxide across the cell membrane. The most frequent answer change for this statement was from unsure pre-intervention to correct post-intervention (39%; 25 students), and the second most frequent answer change was from incorrect pre-intervention to correct at post-intervention (36%; 23 students). Therefore, 73% of students changed their answers from either unsure or incorrect pre-intervention to correct post-intervention, suggesting that most students increased their understanding in this topic. Additionally, several (14) mentions of the free movement of carbon dioxide were present in the 'increased understanding' theme identified in the thematic analysis (Section 4.3.1.1.3.2), supporting the findings for this statement.

Comparing the answer changes by condition for this statement, more haptic students changed from incorrect to correct (17 haptic, 6 non-haptic) and more non-haptic students changed from unsure to correct (17 non-haptic, 8 haptic). However, these changes can be explained by the proportion of haptic and non-haptic students who answered correctly or as unsure pre-intervention, therefore, no notable differences between condition could be determined.

5.2.2.5.4 Statement 10: The cell membrane contains about 5 glucose channels

Statement 10 referred to the nature of the model in relation to the cell membrane and was implemented to determine whether students grasped that the model was a small part of the membrane overall. Most frequently, Statement 10 was answered as unsure both pre and post-intervention (38%; 24 students). 19% (12 students) of students changed from unsure pre-intervention to correct post-intervention, but 13% (8 students) also changed from unsure to incorrect. This would suggest that there was confusion over the nature of the model in relation to the cell membrane, and there is evidence that some students may have had a misconception introduced to them regarding this topic (discussed further in Section 5.2.2.7.2). However, 19% changed from unsure to correct after completing the intervention activity, showing that some students increased their understanding.

Comparing the answer changes by condition for this statement, more haptic students changed from unsure to incorrect (6 haptic, 2 non-haptic). However, these changes can be explained by the proportion of haptic and non-haptic students who answered unsure at pre-intervention, therefore, no salient differences between condition could be determined.

5.2.2.5.5 Statement 11: If there is an equal amount of oxygen inside and outside the cell it will be harder for oxygen to enter than if there is more oxygen outside

Statement 11 concerns the passive diffusion of oxygen down a concentration gradient. The most frequent category was correct both pre and post-intervention (30%; 19 students), but next most frequent answer change was unsure pre-intervention to correct post-intervention (14%; 9 students). However, there was little distinction between subsequent answer change categories.

These results suggest that although some students had an existing understanding of the free movement of oxygen across a concentration gradient, there is evidence of some students increasing their understanding from being unsure pre-intervention and answering correctly post-intervention. However, the few distinctions between remaining categories show that there was still confusion on this topic for some students after the activity was completed (see Table 30).

Comparing answer changes by condition, more haptic students changed from an incorrect answer pre-intervention to an unsure answer post-intervention (4 haptic, 1 non-haptic). However, this difference can be explained by a larger number of haptic students answering incorrectly at pre-test. Similar numbers of haptic and non-haptic students answered unsure pre-intervention (9 haptic, 10 non-haptic) but more haptic students changed from an unsure answer at pre-intervention to incorrect at post-intervention (5 haptic, 0 non-haptic). This would suggest that haptic students may have been more likely to have a misconception introduced during the intervention. This finding is contrary to what the literature would suggest, which is discussed further in Section 5.2.2.8.

5.2.2.5.6 Statement 12: If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside

Statement 12 concerns the passive diffusion of carbon dioxide down a concentration gradient. The most frequent answer category was unsure both pre and post-intervention (22%; 14 students). The second most frequent was incorrect pre-intervention to correct post-intervention (17%; 11 students), which suggests that for these students, there was evidence of increased learning. However, there was little distinction in the numbers of students populating the remaining answer change categories (see Table 32), suggesting that overall there was confusion in the sample regarding this concept.

Comparing answer changes by condition, more haptic students changed from a correct answer pre-intervention to an unsure answer post-intervention (3 haptic, 0 non-haptic). However, this difference can be explained by a larger number of haptic students answering correctly pre-intervention. However, similar numbers of haptic and non-haptic students answered incorrect pre-intervention (11 haptic, 12 non-haptic) but more haptic students changed from an incorrect answer at pre-intervention to correct at post-intervention (7 haptic, 4 non-haptic). Although it is a small difference, it is possible that haptic students may have been more likely to correct an existing misconception during the intervention, which corroborates with what the literature would suggest. Although tentative, this finding is discussed further in Section 5.2.2.8.

5.2.2.5.7 Summary for increased learning and challenging existing misconceptions

In summary, the findings of the true/false/unsure question analysis identified evidence of increased learning and challenging of misconceptions for the concepts of the free movement of oxygen and carbon dioxide across the cell membrane, the selective permeability of the membrane, glucose transport and the nature of the model in relation to the cell membrane. The evidence of increased learning supports the results of the previously mentioned ANOVA (Section4.2.5), which showed that the sample increased their cell knowledge test score after completing the activity. Additionally, the thematic analysis also supports these findings, as the concepts identified as areas of increased learning in the true/false/unsure question analysis were also mentioned in the 'increased understanding' theme (Section 4.3.1.1.3.2). These findings are consistent with what the literature would suggest, which is that an interactive learning environment which allows interaction, exploration, and the testing of hypotheses have the potential to increase germane cognitive load and facilitate deep learning (Asikainen & Gijbels, 2017; Moreno et al., 2001; Vandewaetere & Clarebout, 2013) (discussed previously in Section 2.4.4), regardless of haptic or non-haptic conditions. Comparisons of the true/false/unsure answer changes between conditions are discussed in Section 5.2.2.8.

5.2.2.6 Evidence of the failure to challenge misconceptions

The true/false/unsure analysis identified some statements where students answered incorrectly both pre and post-intervention, which would suggest a failure to challenge their existing misconceptions on that topic. These statements will be discussed below.

5.2.2.6.1 Statement 2: The cell membrane is fluid

Statement 2 referred to the fluidity of the cell membrane, and for this statement, students answered incorrectly both pre and post-intervention most frequently (47%; 30 students). Some students therefore, had an existing misconception that the cell membrane was not fluid before the intervention, but the intervention did not challenge that misconception for a large portion of the students. The fluidity of the membrane was identified as a common misconception in cell biology by Storey (1990), who stated that general biology textbooks often fail to demonstrate that the membrane is not static, but a fluid, dynamic system. These findings therefore correspond with previous literature.

It was not expected that the model would correct any misconceptions on the fluidity of the membrane however, as the model was not programmed to demonstrate fluid movement of the membrane visually or haptically. However, the fluidity of the membrane was discussed as a feature of the cell membrane during model development, and was also identified as a possible source of confusion in the focus group of PGCE biology students in Pilot 5 (Section 3.3.6). The implementation of a fluid membrane in the model was a complex design problem which was not able to be addressed for the main study (discussed in Section 3.4.2). Therefore, modelling of the fluidity of the cell membrane remains a consideration for future design.

Comparing the answer changes by condition for this statement, more non-haptic students changed from unsure to incorrect (2 haptic, 6 non-haptic). 16 students answered unsure pre-intervention: 7 haptic and 9 non-haptic. Therefore, although two more participants in the non-haptic sample answered as unsure, this does not fully account for the difference between conditions for those who changed to an incorrect answer. This small difference may suggest an advantage for the haptic condition in avoiding the introduction of a misconception about the fluidity of the cell membrane. However, the cell membrane in the model was not haptically or visually programmed to be fluid, and therefore there is no clear reason why a discrepancy in the condition may be shown for this statement. It is probable that this difference between conditions is not due to experimental factors and therefore is not noteworthy in this case.

5.2.2.6.2 Statement 3: The cell membrane contains membrane proteins that sit in a fixed position in the membrane

Statement 3 refers to membrane proteins and their movement in the fluid membrane. The aim for this statement was to assess whether the students understood that the membrane proteins were not fixed in position in the membrane but were floating freely within it. The most frequent answer was incorrect both pre and post-intervention (41%;

26 students) with the second most frequent changing from unsure at pre-intervention to incorrect post-intervention (25%; 16 students). This suggests that over a third of students held an existing misconception that membrane proteins sit in a fixed position and did not correct their misconception after participating in the intervention. This is supported by the 'misunderstandings' theme identified in the thematic analysis (Section 4.3.1.2.9), which found multiple comments from students suggesting that membrane proteins are fixed within the membrane. The failure to challenge the fixed membrane protein misconception may be related to the misconception that the membrane itself is rigid and fixed. As discussed in Section 5.2.2.6.1, the fluidity of the membrane was not represented in the model, and 47% of students held the misconception that the cell membrane was not fluid both pre and post-intervention. Should students hold the misconception that the cell membrane is rigid, their perceptions of the proteins residing within the membrane may have also been affected, propagating the misconception that proteins are fixed in place.

Comparing the answer changes by condition for this statement, more non-haptic students changed from unsure to correct (0 haptic, 5 non-haptic) and more haptic students answered incorrectly both pre and post-intervention (20 haptic and 6 non-haptic). However, these changes can be explained by the number of haptic and non-haptic students who answered as incorrectly and as unsure at pre-test and therefore, no salient differences between conditions could be determined from this cell knowledge test data. This finding contrasts with the thematic analysis (Section 4.3.1.2.9), which found that more non-haptic students expressed this misconception during interviews than haptic students. However, as discussed in Section 4.3.1.2.9, this finding from the thematic analysis should be considered tentatively due to the small difference in numbers between conditions, and therefore it is likely that there are few notable differences between conditions for this statement.

5.2.2.6.3 Summary for failure to challenge misconceptions

In summary, the findings of the true/false/unsure question analysis identified evidence of a failure to challenge existing misconceptions for some students. The findings suggest that the misconception that the cell membrane is rigid was not addressed in the activity, but this was expected as the membrane was not programmed to act fluidly. However, the misconception that the membrane proteins sit in a fixed position in the membrane was not challenged successfully during the intervention for over a third of students. This was not expected, as the membrane proteins were not programmed to be in a fixed position. It is possible that the misconception that the membrane is rigid may have affected the students' perceptions of the membrane proteins, therefore failing to dispel the misconception that they are fixed in place. This misconception was not challenged for some students but there is evidence that it may have been introduced to others. The introduction of the fixed membrane protein misconception is discussed in Section 5.2.2.7.1.

5.2.2.7 Evidence of the introduction of misconceptions

The analysis identified some evidence of the introduction of misconceptions during the intervention. This evidence comes from statements where students answered either correctly or as unsure pre-intervention but answered incorrectly post-intervention. Statements which show evidence of possible misconceptions being introduced are discussed below.

5.2.2.7.1 Statement 3: The cell membrane contains membrane proteins that sit in a fixed position in the membrane

Statement 3 was previously discussed in Section 5.2.2.6.2, as most frequently, students answered incorrectly both pre and post-intervention (41%; 26 students), suggesting that an existing misconception was not challenged by the intervention for some students. However, second-most frequently, students answered unsure pre-intervention and incorrect post-intervention (25%; 16 students). This would suggest that a misconception that proteins sit in a fixed position in the membrane may have been introduced to a quarter of students. However, the introduction of this misconception was not expected, as the proteins in the model were able to be manipulated and moved within the membrane using the haptic interface.

The proteins were not programmed to move independently but would show free movement within the membrane when manipulated. As discussed previously (Section 4.3.1.2.9), the haptic feedback allowed students to feel the movement of the membrane proteins as they were manipulated, whereas the non-haptic students would have only experienced visual stimuli. As discussed in Section 2.4.5, the modality-appropriateness hypothesis (Welch & Warren, 1980) would suggest that when haptic information is most accurate for a task, it will be favoured over other senses. Therefore, if visual information was not sufficient to show that the membrane proteins were not fixed in place, the modality-appropriateness hypothesis (Welch & Warren, 1980) would suggest that those in the haptic condition would have been able to use the more accurate haptic information to feel the movement of the membrane proteins in the model. However, whether students were in the haptic or non-haptic condition did not seem to affect whether the fixed protein misconception was introduced, as an equal number of students from non-haptic and haptic conditions changed from either unsure or correct pre-intervention to incorrect post-intervention (10 haptic, 10 non-haptic). In contrast, the thematic analysis (Section 4.3.1.2.9) found that slightly more non-haptic students expressed the fixed membrane protein misconception during interviews than haptic students, but as discussed in Section 4.3.1.2.9, this finding from the thematic analysis should be considered tentatively. Therefore, the findings for Statement 3 and the thematic analysis suggest that there is insufficient evidence for notable differences between conditions for the introduction of this misconception.

As discussed in Section 5.2.2.6.2, it is possible that the ‘rigid membrane’ misconception (Section 5.2.2.6.1) may have influenced students’ perceptions of the proteins within the membrane. Additionally, although those in the haptic condition were provided with haptic feedback concerning the movement of the proteins, it is possible that some students may not have perceived that information, therefore explaining the lack of differences between conditions for Statement 3. For example, it is possible that some haptic students did not interact with the membrane proteins in the model as intended (e.g. hitting rather than grasping molecules to pass through the membrane channels) and therefore did not perceive the haptic feedback regarding the protein movement. Further studies could examine the video data of the activities to determine how students interacted with the haptic components, and further explore how this misconception was propagated.

5.2.2.7.2 Statement 10: The cell membrane contains about 5 glucose channels

Statement 10 was discussed in Section 5.2.2.5.4, as 19% (12) of students changed from unsure pre-intervention to correct post-intervention, suggesting increased learning for this topic. However, 13% (8 students) also changed from unsure to incorrect. As discussed in Section 5.2.2.5.4, Statement 10 was implemented to determine whether students grasped that the model was a small part of the membrane overall, and therefore, students changing from unsure to an incorrect answer would suggest the introduction of a misconception of the nature of the cell model in relation to the membrane. Additionally, for this statement, the most frequent answer category was unsure both pre- and post-intervention (38%; 24 students). Therefore 50% (32) of students for this statement answered unsure pre-intervention and either unsure or incorrect post-intervention. This would suggest that there was confusion over the nature of the model in relation to the cell membrane and that students may have not fully grasped that the model was a small part relative to the membrane. This may be an issue with understanding the size/scale of the cell and its components. As discussed in Section 2.1.2.1.1, Flores et al. (2003) identified size and scale as a common category of misconceptions in their research, where they found that students had problems with recognising a variety of cell forms and size. It is possible therefore, that misconceptions on the size/scale of the model in relation to a cell membrane may need to be considered in future research. During development of the model in this study, there were discussions on implementing an introductory animation magnifying from a larger scale down to the cell membrane to add context to the model. However, implementing this in the VR was expected to be time consuming in the activity and potentially an unnecessary distraction from the task. Instead, to add context, a diagram of a cell was added to the beginning of the worksheet (Appendix DD) showing the model as part of the cell. However, the findings for Statement 10 suggest that this worksheet information was inadequate for some students in this study.

Comparing answer changes by condition, more haptic students changed from either unsure or a correct answer pre-intervention to an incorrect answer post-intervention than non-haptic (7 haptic, 3 non-haptic). However, this can be explained by more haptic students answering either unsure or correct pre-intervention than non-haptic students, suggesting no notable differences between conditions on the introduction of this misconception.

5.2.2.7.3 Summary for the introduction of misconceptions

In summary, the analysis of the true/false/unsure section of the cell knowledge test found evidence for the introduction of misconceptions during the learning activity. Misconceptions that the analysis suggests were introduced include that proteins sit in a fixed position in the membrane and that there are about 5 glucose channels in the membrane, with no notable differences found between conditions. Potential reasons for the misconception of the fixed membrane proteins include that the ‘rigid membrane’ misconception (Section 5.2.2.6.1) may have influenced students’ perceptions of the proteins within the membrane, and that students may not have directly manipulated the proteins within the model to demonstrate their fluid position in the membrane. It was suggested that video recordings of the activities could be used to explore this further. The introduction of the misconception that there are about 5 glucose channels in the cell membrane suggests that the students did not understand the nature of the model in relation to the cell membrane overall, and that the diagram used in the main study worksheet may not have been sufficient for some students to appreciate the model as a small part of the whole membrane.

5.2.2.8 Comparison between haptic and non-haptic conditions

The analysis of the true/false/unsure answers was separated by condition to determine differences in how students changed their answers depending on whether or not they received haptic feedback during the intervention. Differences between the conditions were discussed in the sections above, but few clear variances were found. This supports the findings of the ANOVA, which showed that there was no significant difference in the learning gains between haptic and non-haptic conditions. This was expected however, as the true/false/unsure questions were part of the overall cell knowledge test score used to calculate the ANOVA.

The results of the true/false/unsure analysis and ANOVA were contrary to what the literature suggested, which was that haptics may be particularly useful for learning abstract concepts where visual information is inadequate (Zacharia, 2015). The concept of the cell membrane concentration gradient fits this description, and therefore it was expected that haptic feedback would be especially beneficial for learning in that topic.

However, analysis of the true/false/unsure section questions relating directly to the concentration gradient found mixed results regarding the effects of haptic feedback. Statements 11 (If there is an equal amount of oxygen inside and outside the cell it will be harder for oxygen to enter than if there is more oxygen outside) and 12 (If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside) were related to passive diffusion across a concentration gradient. Comparing conditions for Statement 11, more haptic students changed from an unsure answer pre-intervention to incorrect post-intervention (5 haptic, 0 non-haptic). Results for Statement 11 therefore suggest that haptic students may have been more likely to have a misconception introduced during the intervention, which is contrary to what the literature would suggest. For Statement 12 however, more haptic students changed from an incorrect answer pre-intervention to correct post-intervention (7 haptic, 4 non-haptic). Results for Statement 12 therefore suggest that haptic students may have been more likely to correct an existing misconception for this topic during the intervention, corroborating with what the literature would suggest. The findings for these two statements were contradictory, but the number of students being compared were also small, which prevents clear conclusions on the effect of condition on the understanding of passive diffusion and concentration gradients.

There are several potential explanations for why haptics was not shown to be beneficial for students in this study. Firstly, it is possible that haptic students did not sufficiently perceive the change in force across the cell membrane as the concentration gradient increased or decreased. As discussed in Section 5.2.1.1, the concentration gradient is thought to be especially suited for the use of haptics in learning, as it is abstract and not sufficiently demonstrated with visual information (Zacharia, 2015). Therefore, if students did not perceive the haptic information regarding the concentration gradient as intended, this may have affected the results of the study. There is some evidence from the true/false/unsure section analysis that suggests that some haptic students did not benefit from the concentration gradient haptic feedback as intended. As discussed in Section 5.2.2.5, statements concerning the concentration gradient (Statements 11 and 12) showed evidence of increased learning for some students, but overall demonstrated confusion on the topic. It is possible that students may have been confused by these statements; however, there is also evidence from the thematic analysis that the haptic feedback regarding the concentration gradient may not have been perceived by some students.

As discussed in Section 4.3.1.1.1.2, it was clear from the interviews that the concentration gradient haptic feedback was not always noted (or at least discussed as frequently) as other haptic feedback (e.g. the weight/hardness of molecules and the membrane). For example, the ‘haptics’ theme (Section 4.3.1.1.1), showed that a smaller proportion of students in the haptic condition discussed the concentration gradient compared to other types of haptic feedback, suggesting that fewer students were aware of its presence in the model. If some students did not perceive the haptic feedback regarding the concentration gradient as intended, and therefore did not benefit their learning in the topic for which haptics is thought to be most suited, this may have had an impact on the results overall.

Additionally, there is evidence that attention to haptic information can be diminished due to the dominance of visual information and excess cognitive load, which offer further explanations for the results of RQ1. How visual dominance and cognitive load can affect the perception of haptic information is discussed further in Sections 5.4.1.1.2 and 5.4.1.1.3.

5.2.2.8.1 Comparison between haptic and non-haptic conditions summary

Overall, few differences were found between haptic and non-haptic conditions in the analysis of the true/false/unsure section of the cell knowledge tests. This corresponds with the results of the ANOVA which showed that overall, there were no significant differences in learning gains between haptic and non-haptic conditions as measured by the cell knowledge test. Some explanations for why haptic feedback was not beneficial for learning in this study (despite support from the literature) were suggested. It was discussed that students may not have perceived the haptic feedback regarding the concentration gradient, which was suggested in the literature to be a topic for which haptics would be beneficial. Evidence from the thematic analysis was discussed, which suggested that although students in the haptic condition may have perceived haptic feedback generally, fewer students mentioned perceiving the haptic feedback from the concentration gradient. It was discussed that if students were not able to utilise haptic feedback to improve their learning in a topic for which haptics is thought to be especially suited for, then this may have affected the results for this study. Additionally, visual dominance and cognitive load theories were mentioned as possible explanations for the lack of benefits seen from the haptic condition, as they have the potential to dampen attention to haptic feedback.

5.2.2.9 Summary and conclusion

The analysis of the true/false/unsure questions from the cell knowledge test took answers for each statement and compared how students' answers changed from pre to post-intervention. Each statement corresponded with the understanding of certain concepts regarding the cell membrane, and therefore an analysis of how students answered each statement both before and after the intervention activity was used to gain insight into the learning or lack of learning in those concepts. The findings of this analysis were discussed in this section.

It has been shown that existing misconceptions were present in this sample, including concepts regarding the selective permeability and fluidity of the cell membrane and glucose transport, fluidity of the movement of membrane proteins and passive diffusion of molecules through the membrane. Selective permeability, fluidity of the membrane and diffusion had been identified in the literature as common topics of misconception in cell biology (Section 2.1.2.1), and therefore the sample chosen for this study was shown to be typical and suitable for the use of an intervention for this topic.

The findings of the true/false/unsure question analysis also identified evidence of increased learning, challenging of misconceptions, failure to challenge misconceptions and the introduction of misconceptions due to the intervention. Evidence for increased learning was found for statements concerning the concepts of the free movement of oxygen and carbon dioxide across the cell membrane, the selective permeability of the membrane/glucose transport and the nature of the model in relation to the cell membrane. The evidence of increased learning supported the results of the ANOVA which showed that overall, there was a significant increase in cell knowledge test scores after the intervention. Additionally, topics of increased understanding identified in the true/false/unsure analysis were also identified in the 'increased understanding' theme of the thematic analysis, further supporting the findings. Increased learning overall was expected in this study, as virtual manipulatives offer manipulation and physicality which have been shown to be beneficial in the learning of science (Section 2.4.2.1.3).

As discussed in Section 2.4.2.1.3, according to Embodied Cognition (Barsalou, 2008), perceptual experiences which are able to be embodied may enable students to build richer multimodal representations (Han, 2013; Zacharia et al., 2012). Therefore, manipulation regardless of haptic feedback can create embodied experiences, but the addition of haptic feedback according to Embodied Cognition would provide additional, unique perceptual experiences with which to ground abstract concepts such as those in cell biology. However, no notable differences between conditions were found in the true/false/unsure question analysis concerning increased learning and challenging of misconceptions, which may suggest that the haptic condition did not provide sufficient additional experiences to be embodied, as discussed previously in Section 5.2.1.1.

Evidence of a failure to challenge some existing misconceptions and the introduction of misconceptions was found from the analysis of the true/false/unsure questions. A misconception that the cell membrane was rigid was identified, but this was not unexpected as the cell membrane was not programmed to move fluidly (Section 3.4.2). However, a misconception that membrane proteins sit in a fixed position was also introduced to a quarter of students. This misconception was not expected, as the membrane proteins were programmed to move when manipulated. It was suggested that the previous 'rigid membrane' misconception may have affected the students' perceptions of the proteins situated within that membrane. It was also suggested that some students may not have interacted with the membrane proteins as intended, as researchers had observed some students hitting the particles rather than grasping and guiding them through the channels. The thematic analysis (Section 4.3.1.1.5.4) found that some students had difficulty in grasping molecules, and therefore it is possible that those students may not have been exposed to the movement of the proteins, mistakenly concluding that the proteins were fixed in place. There were also no clear differences in this misconception between haptic and non-haptic conditions. According to the modality-appropriateness hypothesis (Welch & Warren, 1980), if visual information was inadequate to show the movement of the proteins, haptic information would have been favoured as it was able to provide more accurate sensory information. However, the lack of differences between conditions for this misconception would suggest that this was not the case. It may be that students from both conditions may not have interacted with the membrane proteins in a way that would allow them to experience the protein movement.

A comparison of the answer changes between haptic and non-haptic conditions for the true/false/unsure answer changes found few clear differences, which corresponds with the results of the ANOVA. Some suggestions as to why there were no benefits of the haptic condition in this case were discussed. Findings from the thematic analysis suggested that not all students noticed the haptic information from the concentration gradient (Section 4.3.1.1.1.1), and as the concentration gradient was the topic most suited to the use of haptics to increase understanding in the activity, a failure to perceive that information may have prevented the benefits of haptics from being demonstrated in this study. Additionally, as discussed further in Sections 5.3.1.1.1 and 5.3.1.3, the thematic analysis found evidence of the effects of visual dominance and excess cognitive load, which have the potential to diminish the beneficial effects of haptic feedback in learning complex concepts (Sections 2.4.4 and 2.4.5). How visual dominance and cognitive load could have influenced the ability of the haptic feedback to benefit learning is discussed further in Sections 5.4.1.1.2 and 5.4.1.1.3..

5.2.3 RQ2 and RQ3

2. Does existing spatial ability have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?

3. Does existing fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?

5.2.3.1 RQ2

As discussed in Sections 2.2 and 2.3, spatial ability has been shown to have an important role in STEM learning, and visualisation in particular allows the modelling of complex scientific concepts, facilitating the understanding of abstract ideas such as those involved in cell biology. Hays' (1996) ability-as-compensator hypothesis would suggest that those with low spatial ability would benefit from graphical representations such as the 3D cell in this project, as they struggle to construct their own. Additionally, research has shown that interacting with 3D models has a positive impact on comprehension of 3D computer visualisations for those with lower spatial ability (Keehner et al. 2004). Conversely, Huk's ability-as-enhancer hypothesis (Huk, 2006) suggested that according to DCT (Paivio, 1969), 3D representation of a cell presents extra graphical information that may overload the visuo-spatial memory of those with low spatial ability, causing a detriment to learning. Consequently, spatial ability was decided to be a potentially important aspect to measure in this project due to its potential ability to influence learning through the 3D haptic environment. This was done with two separate spatial ability tests: the SRT (Levy & Levy, 1999) and the WISC-IV BDT (discussed in Section 3.4.6.1). These tests measured spatial visualisation and orientation, which were thought to be relevant to the use of graphical and 3D representations (Section 3.3.3.3.3).

To answer RQ2, the SRT, BDT and combined scores of the two spatial tests were used as covariates in a mixed ANCOVA. Three mixed ANCOVAs were conducted to determine any statistically significant difference between haptic and non-haptic groups on their change across time points, controlling for spatial ability scores. The ANCOVAs showed that there was no significant effect of condition on the increase of participants scores across pre-intervention, post-intervention, and retention-tests. Additionally, the mixed ANOCVA showed that no spatial ability scores were identified as a significant covariate for the change in knowledge scores across pre-intervention, post-intervention, and retention-tests. Spatial scores were normally distributed, meaning that there were no skews in the scores towards the high or low end. Therefore, the findings show that spatial ability was not shown to influence students' change in knowledge across time points. This would suggest that having either low or high pre-existing spatial ability scores did not influence how well students increased their knowledge scores in the short (pre to post-intervention) or longer term (post-intervention to retention-test).

Although the literature reports mixed findings (Section 2.2.2), there may be some gender differences in spatial ability (Maccoby & Jacklin, 1974), suggesting that it may be an issue to consider when developing learning strategies in these subjects. However, in this study no significant differences were found in spatial scores between male and female participants, and therefore spatial differences according to gender were inconsequential in this case. As discussed in Section 2.2.2, there is evidence that although there is a male advantage in spatial perception and mental rotation, spatial visualisation is equally difficult for males and females (Linn & Petersen, 1985). Spatial visualisation was a relevant subset of spatial ability in this project and was measured in both tests of spatial ability (Section 3.3.3.3). The lack of gender differences in spatial visualisation found in the literature and the ability for students to manipulate 3D objects physically within the learning environment rather than rely on mental rotation may therefore help explain the lack of gender differences in this study. It is also possible that no gender differences were detected in this study for spatial visualisation as all students attend selective, private schools and therefore are not from a typical population (discussed further in Section5.7).

Although the literature suggests that spatial ability may be implicated in learning with graphical representations, the results of the mixed ANCOVAs do not support the ability-as-compensator (Hays, 1996) or ability-as-enhancer (Huk, 2006) hypotheses. These results therefore suggest that spatial ability was not a major factor in using the specific 3D haptic system developed for the main study. Although spatial scores were normally distributed amongst the sample and showed a large variance of scores around the mean (Section 4.2.6), it is possible that the sample size may have been too small to pick up a significant effect of spatial ability, as lower sample sizes can increase the likelihood of a false negative result (Banerjee, Chitnis, Jadhav, Bhawalkar, & Chaudhury, 2009).

5.2.3.2 RQ3

As discussed in Section 3.3.3.3.2, previous studies had identified fine dexterity as a skill relevant to the use of stylus based haptic systems, and the Morrisby Fine Dexterity test was identified as a suitable measure (Shahriari-Rad, 2014). Although the development of the learning environment's method of navigation moved away from a stylus to a multi-fingered method for the main study, fine dexterity was still required to navigate the 3D space. It was thought that differences in fine dexterity may have been able to affect how students interacted with the system, or how well they could navigate the 3D space. For example, those with low fine dexterity may have had more issues grasping or moving parts of the cell membrane model or may have needed to allocate more working memory resources to the navigation of the space, increasing their extraneous cognitive load. Therefore, it was decided by the project team that fine dexterity should be measured as a possible variable relevant to the study. The Morrisby Fine Dexterity test comprised of a tweezer and finger portion. Where the tweezer portion of the test was relevant for testing fine dexterity in relation to stylus-based haptic devices, the finger portion required students to use their thumb and forefinger in a manner similar to what was required for the multi-fingered device. Therefore, the Morrisby Fine Dexterity test was a suitable method for testing fine dexterity in this study.

To answer RQ3, fine dexterity scores (finger, tweezer, and combined scores) were entered as covariates in three mixed ANCOVAs. The ANCOVAs showed that regardless of which covariates were included in the ANCOVA, there was a significant increase of scores across time points and no significant effect of condition. This means that regardless of which fine dexterity score was used, participants significantly increased their scores after using the system, but there was no effect of haptic feedback in the gain in knowledge.

The analysis showed that fine dexterity tweezer scores were not identified as a significant covariate for the change in knowledge scores across pre, post and retention time points. However, it was found that the scores for the finger portion of the fine dexterity test was a significant covariate. Therefore, condition (haptic or non-haptic) did not significantly affect the change in knowledge scores for these participants, but finger fine dexterity scores were found to affect the change in score over time (across pre, post and retention time points). Exploring further, a Pearson's r correlational analysis was conducted, which showed that there was a significant negative association between score difference from post-intervention to retention-tests and finger fine dexterity, but no significant association between score difference from pre to post-intervention, suggesting that the association between finger fine dexterity and change in tests scores originates from the difference between post-intervention and retention-test scores. Therefore, finger fine dexterity was not shown to significantly affect the change in scores from pre to post-intervention time points but was shown to affect the retention of the knowledge they had gained.

It was expected that should there be a significant correlation between fine dexterity and retention of knowledge that it would be positive. However, the negative correlation shows that those with lower fine dexterity seemed to retain more of their knowledge. Possible reasons for why fine dexterity may have been detrimental to retaining knowledge in this study may include the amount of time taken by students to interact with the model and to complete tasks. Those with lower fine dexterity may have spent more time moving the molecules within the model than those with higher fine dexterity, which may have resulted in more exposure to experiences during the task which could be embodied. As discussed in Section 2.4.2.1, according to Embodied Cognition (Barsalou, 2008), multiple sensory modalities experienced during learning are integrated to create a multimodal representation stored in memory, which can create cognitive anchors for understanding abstract concepts (Reiner, 2009). The potential for creating embodied experiences has been shown to also be important for increased learning (Han, 2013; Zacharia & Olympiou, 2011), and therefore it is possible that if students spent longer and had more chances to create embodied experiences during the task, they may have retained more of their knowledge. Additionally, if lower fine dexterity had slowed down the activity for some students, this may have resulted in increased thinking or collaboration, as there would have been more time to consider the learning content and discuss the topic with their partner. As discussed in Section 4.3.1.1.5.4, the thematic analysis identified that some students described difficulties in grasping particles within the model (mentioned in 22/31 interviews). Although the difficulties in grasping particles was not detrimental enough to dampen the students' enjoyment of the activity (as shown in the 'praise for the system' theme-Section 4.3.1.2.1) or stop the sample learning overall during the intervention activity (Section4.2.5), the prevalence of the 'grasping particles' theme (Section 4.3.1.1.5.4) suggests that some students may have spent more time manipulating particles in the model than others. It could be possible that those with lower fine dexterity may have had more difficulties grasping molecules and therefore spent longer interacting with the system. Although that analysis is outside the scope of this thesis, it may be a point to consider in further studies.

However, it is known that students had received lessons in the topic of cell biology in the time between post-intervention and retention-tests, and therefore it is also possible that newly acquired knowledge may have affected the relationship between fine dexterity and retention of knowledge in this study. Topics of the curriculum covered in lessons in the eight-month period between the post-intervention and retention-tests included the structure of cells, cell specialisation and movement of substances into and out of cells, including an introduction to diffusion and osmosis in the cell. As such, the finding that finger fine dexterity is associated with increased retention of knowledge should be treated with caution, as there is the possibility that uncontrolled variables in their learning experiences between the post-intervention and retention time points may have affected their retention also.

As discussed in Section 3.3.3.5.1.2, the finger portion of the Morrisby Fine Dexterity test involved picking up small parts using the thumb and forefinger, which mirrors the use of the multi-finger haptic device, operated with the thumb and forefinger as contact points. It follows therefore, that the ANCOVAs (Sections 4.2.6.4 and 4.2.6.5) found the finger fine dexterity and not the tweezer dexterity scores to have a significant correlation with retention. In future studies therefore, the tweezer portion of the Morrisby Fine Dexterity test may not be required for use with multi-fingered haptic devices such as that used in this study.

To answer RQ3, fine dexterity did not have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment in the short term (from pre to post-intervention), but for longer term learning (retaining knowledge from post-intervention to retention-tests) finger fine dexterity was found to affect the relationship between the change in knowledge scores and the presence of haptic feedback. Although the presence of haptic feedback was not found to be significant in this study, these results suggested that fine dexterity may be a factor to consider in further research.

5.2.4 Quantitative analysis summary and conclusion

The quantitative analysis discussion has described the findings of the ANOVAs, ANCOVAs and true/false/unsure answer change analyses, and how they contributed to answering RQ1, RQ2 and RQ3.

Firstly, the mixed ANOVA showed that, overall, the sample did increase their understanding of cell biology as measured by the cell knowledge tests. The answer changes from pre to post-intervention of the true/false/unsure questions identified existing misconceptions in the sample pertaining to concepts of the selective permeability and fluidity of the cell membrane/glucose transport, fluidity of the movement of membrane proteins and passive diffusion of molecules through the membrane. The true/false/unsure question analysis also corroborated the ANOVA by demonstrating a lack of differences between conditions, but an increase in knowledge overall. The analysis identified concepts for which students demonstrated increased understanding, which included free movement of oxygen and carbon dioxide across the cell membrane, the selective permeability of the membrane/glucose transport and the nature of the model in relation to the cell membrane. The true/false/unsure question analysis also identified evidence of confusion regarding the concentration gradient, which together with evidence from the thematic analysis (Section 4.3.1.1.1.1) may suggest that haptic feedback regarding the concentration gradient was not always noted by students in this study.

To answer RQ1, the mixed ANOVA showed that haptic feedback within the context of a collaborative, 3D learning environment did not enhance learning of complex concepts in cell biology compared to no haptic feedback. This is contrary to the literature, which would suggest that adding the haptic sense to learning in this topic would have a beneficial effect. Some reasons as to why the results of this study did not reflect what the literature might suggest were discussed, including the perception of haptic feedback, the effect of excess cognitive load on the working memory and the effect of visual dominance, which are discussed further in Sections 5.3.1.1 and 5.3.1.3.

To answer RQ2 and RQ3, mixed ANCOVAs showed that existing spatial ability and tweezer fine dexterity did not have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment, but finger fine dexterity was found to significantly influence the retention of knowledge through a negative association. Reasons for this association include the possibility that students with lower fine dexterity may have taken longer during activities and therefore reaped more benefits from interacting with the system. However, the presence of classroom learning in cell biology between post-intervention and retention time points requires that this finding should be considered with caution.

The next section discusses the qualitative thematic analysis of the semi-structured interviews (Section 4.3) which is used to answer RQ4 (*what design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?)*.

5.3 Qualitative analysis

Section 5.2 discussed the results of the quantitative analysis from the main study, which were used to answer RQ1, RQ2 and RQ3. RQ4 however required a qualitative approach and was explored using open coding and thematic analysis of semi-structured interviews (as described in Section 3.4.8.6). The qualitative analysis described in Sections 3.4.8 and 4.3 were used to answer the following research question:

4. What design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?

This section will discuss the findings from the qualitative analysis (Section 4.3), including the meaning of the findings in relation to RQ4.

5.3.1 Thematic analysis discussion: results in relation to theory

For the thematic analysis, some discussion was presented in the results chapter (Section 4.3.1) for each theme, summarising the findings and the possible implications for previously mentioned theories. Theories that were implicated in these discussions included CLT (Sweller, 2011), the modality-appropriateness hypothesis (Welch & Warren, 1980) and the directed-attention hypothesis (Posner et al., 1976). This section will discuss these theories and how the findings of the thematic analysis relate to them in more detail.

5.3.1.1 Cognitive load during the intervention

As discussed in Section 2.4.2.2, CLT (Sweller, 1994) suggests that whilst learning, an individual's working memory is put under cognitive load as new information is attempted to be processed. The theory is based on the 'modality principle' (Millar, 1999), which assumes that every modality has its own processing channel within working memory and that by utilising several channels, cognitive load can be split between them in order to be decreased, thereby facilitating learning.

Cognitive load is separated into three categories according to Sweller (2011): intrinsic, extraneous, and germane (discussed previously in Section 2.4.4). Intrinsic cognitive load occurs from the information being learned and extraneous cognitive load is imposed by how the information is presented. Germane cognitive load refers to the cognitive resources used and mental strain of constructing schemas and processing information to long term memory. Therefore, for learning to occur, germane load must be promoted. An excess of cognitive load however can overload the working memory and negatively impact learning.

As discussed previously, cell biology is known to be complex and difficult to learn (Section 2.1), and therefore imposes implicit cognitive load. As discussed in Section 2.3.3, DCT (Paivio, 1969) suggests that using the haptic sense in learning this complex information can utilise the haptic modality and its processing channel to more effectively process the information. In the case of learning cell biology in this project therefore, multiple modalities (i.e. the use of visual and haptic stimuli) were used to lower the intrinsic cognitive load on the working memory and aid the learning of complex information.

However, the instructional design of the presentation of this complex information affects how much extraneous cognitive load is added to the students' working memory. Instructional design can also affect germane load, as enjoyment and motivating activities (which can be fostered through new or interesting ways of presenting information) can make students more likely to invest in germane load for their learning (Van Merriënboer & Sweller, 2005).

Although using the haptic channel was intended to lower cognitive load during the main study and aid learning, the findings from the thematic analysis revealed several sources of extraneous and germane cognitive load which the literature suggests may affect the ability of students to process complex information (Sweller, 2011). Relevant findings from the thematic analysis concerning cognitive load will be discussed here as well as the implications for excess cognitive load on students' learning in this study.

5.3.1.1.1 Extraneous load during the intervention

The findings of the thematic analysis identified potential sources of excess cognitive load during the intervention, which will be discussed in this section.

5.3.1.1.1.1 Effects of novelty on cognitive load

The findings of the thematic analysis suggested that some themes exposed possible sources of extraneous cognitive load. The learning environment that the students used to interact with the cell model in VR was a novel experience. The literature suggests that novel ways of presenting information exerts extraneous cognitive load as students navigate how to use the system and make sense of the information simultaneously (Sweller, 1994). The literature suggests therefore, that the way the information was presented in this case may have exerted extraneous load on the working memory of the students. Although the multi-finger system movement was intuitive within the virtual space, it is likely that learning how to manipulate the virtual space would have incurred cognitive load to the pilot. The 'grasping particles' theme discussed in Section 4.3.1.1.5.4 would suggest that some students had difficulty in this regard, and although this difficulty did not seem to affect the students' ability to complete the task (as demonstrated by the worksheet completion: Appendix RR), it was noted by some students as something to overcome in their use of the system. As discussed in Section 4.3.1.2.3, to lower the effect of novelty of the system on students, it is possible that exposure to the system before the experiment to a level of familiarity could be beneficial. This was not possible in the case of this project, as the timeline of development for the system (Section 3.3) did not allow extensive practice to take place in schools. However, the findings from the thematic analysis also found that students found the novelty of the system appealing, which may have helped students allocate processing resources from their working memory to their task (discussed further in Section 5.3.1.1.2).

5.3.1.1.1.2 Difficulties using the learning environment

Another possible source of extraneous cognitive load were the difficulties students described encountering when using the system. The ‘difficulties’ theme (Section 4.3.1.1.5) collated comments from students on what they found difficult about using the system, and sub-themes that emerged were ‘technical problems’ (which included freezing and glitches), ‘thimble issues’, ‘task difficulty’, ‘grasping particles’ and ‘space restriction’. ‘Technical problems’ usually took the form of students losing their cursors in the virtual space or the system freezing and needing to be restarted. Although these issues may have interrupted their tasks momentarily as they restarted the program, the interruptions did not seem to influence the students’ ability to complete the activity worksheet (as seen in Appendix RR). However, the ‘grasping particles’ theme did show that some students had some difficulty, at least initially, with grasping particles in the virtual space, which may have increased the extraneous cognitive load on their working memory. Observations of the activity supports this as a possible factor, as some students were observed by researchers to have problems grasping the molecules properly during the activity. Learning how to manipulate the particles with the VR learning environment was not a task that directly added relevant haptic information on the topic of the cell membrane, and therefore was cognitive load extraneous to the learning goals. Those in the haptic group had fewer items of data coded to the ‘grasping molecules’ sub-theme (17 haptic versus 26 non-haptic) suggesting that perhaps those in the haptic condition found manipulating the particles easier. However, there were more items of data coded in the ‘task difficulty’ sub-theme from the haptic condition (21 haptic versus 9 non-haptic), meaning that those in the haptic condition were more likely to describe the task as difficult. With more students in the haptic condition describing the task as difficult despite potentially finding the grasping of molecules easier, this may support the assertion that the addition of the haptic feedback may have increased cognitive load, influencing their perceptions of the difficulty of the task.

5.3.1.1.1.3 Summary and conclusions

It was discussed in Section 2.4.3 that haptics may be beneficial for information which cannot be adequately explained visually (Zacharia, 2015), and a haptic system may have the ability to lower extraneous load by providing access to haptic information relevant to learning. A well-designed presentation of learning content can lower extraneous load by facilitating the access to relevant information needed for efficient processing of complex information. In this project, the haptic system provided haptic information which was not able to be conveyed easily through visual means (e.g. the forces of the concentration gradient). However, it could be argued that for other haptic tasks during the activity (such as moving molecules), the information could have been conveyed sufficiently through visual information. If this was the case, then extra haptic information may have increased the extraneous cognitive load on the student without the benefit of lowering the intrinsic cognitive load through the modality principle, thus putting undue burden on the working memory.

In Section 4.2.7, the changes in the true/false/unsure question answers from pre to post-intervention were presented for each statement. The answer changes for concentration gradient related questions seen in Section 4.2.7 and the 'concentration gradient' theme identified in the thematic analysis in Section 4.3.1.1.1.1 suggested that not all students exhibited increased learning on this topic with the addition of haptic feedback. The increased extraneous cognitive load from the method of interaction coupled with visual dominance effects (Section 2.4.5) may contribute explanations for the mitigated effect of the haptic feedback on students' learning for this topic.

5.3.1.1.2 Germane Load

As discussed in Section 2.4.4, within CLT (Sweller, 1994) germane load describes the load used for the construction of mental representations from learning materials needed for processing information to store in long-term memory (Skulmowski et al., 2016). Germane load can include organising material, relating it to prior knowledge by referring to schemas or constructing new schemas. For ideal learning conditions for information high in intrinsic cognitive load (as with complex topics like cell biology), germane load should be fostered, and extraneous load should be minimised (see Section 5.3.1.2 for more detail).

As discussed in Section 2.4.2.2, if an activity is designed in a way that students enjoy and are motivated by, they may be more likely to invest in germane load for their learning (Van Merriënboer & Sweller, 2005). The findings from the thematic analysis suggested that students generally enjoyed the intervention. The ‘praise for the system’ theme consisted of comments regarding enjoyment and engagement, and the ‘liked features’ theme identified a range of aspects of the system that students enjoyed. Additionally, in the ‘comparison with regular teaching’ theme it was clear that the students preferred interactive learning over normal teaching methods. The findings of this study mirror that of Hallman et al. (2009) (discussed previously in Section 2.4.3), who found that although adults were generally negative about the use of haptics in learning the topic of gears, children were more comfortable with the use of technology and found haptics to be enjoyable and constructive to their learning. The ‘praise for the system’ and ‘liked features’ themes identified in the thematic analysis suggest that as with Hallman et al. (2009), students enjoyed their experience and expressed curiosity and interest. Hallman et al. (2009) suggested that involving students in an exciting and interesting activity can result in a more productive educational process, which corresponds with the beneficial effects of germane load described in CLT (Sweller, 2011). Overall, these findings from the thematic analysis showed that the students enjoyed the system and were motivated to use it. This would suggest increased germane cognitive load, as they were more likely to allocate working memory resources to their activities.

Intrinsic, extraneous, and germane cognitive loads interact with each other to form the overall cognitive load on the working memory. Intrinsic load comes directly from the complexity of the information needing to be processed, and after working memory resources are allocated to deal with this intrinsic load, remaining resources can be allocated to extraneous and germane load (Cook, 2006). Both extraneous and germane load can also be altered with the use of instructional design (the way the information is presented), because if extraneous load is lowered due to instructional design, then more resources can be allocated to germane load to the benefit of learning. However, during the learning of complex information when intrinsic load is high, schema formation can be more difficult, requiring a higher germane load. Therefore, when intrinsic load is high (as was the case in this study), extraneous load becomes more impactful as it takes up resources needed for processing and the creation of schemas. Therefore, although the findings of the thematic analysis would suggest that students may be more likely to invest in germane load, an addition of high intrinsic cognitive load means that excess extraneous load has the potential to overburden the students' working memory.

5.3.1.2 Balancing cognitive load

In Section 5.3.1.1, the findings of the thematic analysis were discussed in relation to the possible increased pressures of extraneous and germane cognitive load on working memory during the activity in this study. However, by design, there were decisions made during the development of the intervention which aimed to decrease cognitive load and ultimately aid learning, guided by previous literature (Chapter 2). These included the use of multiple modalities and collaborative learning. In this section, aspects of the activity that the literature suggests may have decreased or increased cognitive load will be reviewed in context with the findings of the thematic analysis.

5.3.1.2.1 Designing to reduce cognitive load

5.3.1.2.1.1 Using haptics to reduce cognitive load

As discussed previously (Sections 2.4.2.2), central theories discussed for why using haptic feedback may benefit learning in cell biology included DCT (Paivio, 1969), CLT (Sweller, 1994) and their mutual reference to the modality principle (Millar, 1999). These theories suggest that haptic feedback is processed in a separate processing channel to other modalities, and that by utilising this channel, the high cognitive load of learning complex biological topics may be reduced and information processed more efficiently, resulting in benefits to learning.

The thematic analysis (Section 4.3.1) gave an indication that students in the haptic condition received and were aware of the haptic feedback, so the system's design was successful in this regard. Evidence for this came from the 'haptic' theme (Section 4.3.1.1.1), which included comments of being able to 'feel' in the system and was populated almost entirely by comments of students in the haptic condition. Supporting this, the 'not able to feel' theme (cataloguing comments that the students could not feel haptic feedback) was also mostly entirely populated by those in the non-haptic condition. However, the quantitative results found no significant difference between the haptic and non-haptic conditions in learning gains (Section4.2.5), suggesting that haptic feedback did not significantly benefit these students' learning of cell biology. The quantitative findings are supported by the findings of the thematic analysis, as the number of items coded to the 'increased understanding' theme (which catalogued instances of increased understanding of the topic, or students' perceptions of increased understanding) were similar in the haptic and non-haptic conditions (55 haptic and 56 non-haptic), suggesting that there was no discernible differences in learning between conditions from the interviews. Haptic feedback was employed to make use of separate processing channels, reduce cognitive load and aid learning. However, as discussed in Section 5.2.1, a gain in learning due to the addition of haptic feedback was not supported in this study.

5.3.1.2.1.2 Physical manipulation

A feature both the haptic and non-haptic students experienced during the activity was the physical manipulation of the cell membrane model in VR. The non-haptic students did not receive the haptic feedback available in the haptic condition but were still able to navigate and manipulate components of the model. As discussed in Section 2.4.2.1.3, physical manipulation has been shown to be useful for learning in science, which has been used as evidence for the use of a separate haptic processing channel to aid learning (Zacharia, 2015). Although the quantitative and qualitative results did not find a significant difference in learning gains between haptic and non-haptic conditions, the findings of the thematic analysis did show a preference for interacting physically with the learning material. The ‘preference for interaction' (Section 4.3.1.2.4.1) sub-theme suggested that students viewed physically manipulating the model directly on their own terms and being allowed to explore the model as positive attributes. The ‘preference for interaction’ sub-theme seemed to show that learning by experiencing the model first-hand and learning directly compared to receiving information passively was a feature that students enjoyed.

Although the results have suggested that using the haptic channel in the activity did not make a significant difference to the students’ learning gains, it is possible that by taking ownership of their learning experience, students may be more likely to invest germane load to process the information. Additionally, the ‘comparison with regular teaching’ theme (Section 4.3.1.2.4) showed that students compared their learning experience to the use of abstract representations such as diagrams or information given by a teacher. As discussed in Section 2.1.3, it has been argued that a departure from a more traditional, abstract representation in the classroom to a more concrete model able to be explored by students directly could help transform abstract concepts to more grounded concepts that are more easily understood (Lakoff, 1990; Odom, 1995). As discussed in the literature review (Section 2.1), cell biology is notoriously difficult for students to grasp because of its abstract nature (Dreyfus & Jungwirth, 1988), so if students believe that the abstract concepts were easier to understand by interacting with the learning material themselves (as the ‘comparison with regular teaching’ theme would suggest), then this would be a positive attribute of the haptic VR system for learning cell biology. Additionally, interaction and exploration are features of learning which have been suggested to have the potential to also facilitate deeper learning (Asikainen & Gijbels, 2017; Moreno et al., 2001; Vandewaetere & Clarebout, 2013) (Section 2.4.4). Previous literature has also suggested that key to the understanding of cell biology is the ability to model abstract and complex content regarding the molecular world (Tibell & Rundgren, 2010), and interacting with a model of the learning material directly may facilitate that.

The findings from the thematic analysis showed that students appreciated the ability to interact with the learning environment, and the literature shows that this may foster germane load, which is necessary for the learning process (Section 2.4.4). Therefore, the literature would suggest that interactivity and physical manipulation in a virtual space would help support learning whilst using a device capable of providing haptic feedback, as demonstrated by the findings of this study (Section 5.2.1).

5.3.1.2.1.3 Collaboration

As discussed in Section 2.4.4, research has discussed the beneficial effects of collaboration on processing complex information by lowering cognitive load on the working memories of individuals. Referred to as ‘the collective working memory effect’, this effect describes how collaborating learners can benefit from the use of each other’s working memory capacity whilst learning by dividing the cognitive load between co-operating working memories (F. Kirschner et al., 2009a). For information that imposes heavy cognitive load, that load can be distributed over several collaborating individuals, allowing more efficient learning. However, the research also described certain costs for collaborative learning, as splitting cognitive load requires the communication of information and co-ordination of tasks, which in turn requires additional cognitive effort which students working alone would not encounter. These 'transaction' costs, if too high, could nullify the effect of collaboration on lowering cognitive load. For complex subjects, the transaction costs would be relatively low compared to the possible learning gains, whereas in simple tasks, the transaction costs would outweigh the need for shared working memory.

As discussed in Section 2.4.4, the evidence for the collective working memory effect of collaboration suggests that collaboration on a complex and cognitively demanding task would be advantageous in allowing multiple working memories to lower the cognitive load. Research has shown that cell biology is a complex and cognitively demanding topic (Section 2.1), and therefore provides a high amount of intrinsic cognitive load. The research on the effect of collaboration on cognitive load discussed previously in Section 2.4.4 would therefore suggest that collaboration would be an appropriate strategy to lower intrinsic cognitive load.

The findings from the thematic analysis showed that learning collaboratively was a frequent theme throughout the interviews (321 items of data from all 31 interviews). In the 'learning collaboratively' theme, students overwhelmingly expressed that they enjoyed collaboration in the task, and the 'communication and discussion' sub-theme showed that students were glad to generate ideas and support each other's learning rather than working alone. The 'barriers to communication' sub-theme showed that some students may have experienced transaction costs in communicating certain aspects of the experience as a pilot due to being isolated in VR, but these comments were from a minority of students (25/321 items of data from the 'learning collaboratively' theme). This advocates that, as the literature would suggest, the benefits of learning collaboratively seemed to outweigh the potential costs in the students' opinion. As discussed in Section 4.3.1.1.2 however, more items of data in the 'learning collaboratively' theme came from the non-haptic condition (131 haptic and 190 for non-haptic), suggesting that learning collaboratively may have been a more prominent feature for non-haptic students. It is possible that non-haptic students needed to collaborate more as the worksheet questions were worded to encourage discussion on how certain tasks 'felt', and therefore non-haptic pairs may have required more collaboration to make sense of the questions and prepare answers. Additionally, those in the haptic condition may have been more pre-occupied with the haptic feedback, making communication and discussion a less prominent feature for discussion during the interviews. Nevertheless, the findings of the thematic analysis suggest that collaboration (in the form of a pilot/co-pilot partnership) is a beneficial design feature for use in interfaces capable of providing haptic feedback to support the learning of difficult concepts in cell biology.

5.3.1.3 Visual dominance

The findings of the thematic analysis revealed a strong influence of the visual stimuli on students. From the 'seeing' sub-theme it was shown that the most commonly liked feature expressed by the students involved visual features of the system, and the 'visualisation' theme showed that students liked being able to view a process without having to imagine it. Additionally, the 'distraction' theme suggested that the visual aspect of the VR may have been a distracting element, as the visual stimuli were interesting and captured the students' attention.

As discussed in Section 2.4.5, there is evidence that, when presented with multiple modalities, the visual sense has been shown to dominate others, an effect called 'visual dominance' (Posner et al., 1976). Two prominent theories regarding visual dominance are the modality-appropriateness hypothesis (Welch & Warren, 1980) and the directed-attention hypothesis (Posner et al., 1976). The modality-appropriateness hypothesis (Welch & Warren, 1980) suggests that, when presented with incongruent information from visual and other sensory information, the sense which allows the greatest precision is favoured. This suggests that visual information is favoured because it is usually the most appropriate for the task (Pye, 2008). However, for information where haptics may provide more accurate information over visual, this hypothesis suggests that haptics would be preferred. Furthermore, Klatzky et al. (1991) suggested that when visual information is adequate for the task at hand, attention may not be attuned to haptic exploration due to its high processing cost relative to its benefits. The directed-attention hypothesis (Posner et al., 1976) suggests that as attention is concentrated toward any one modality, there is a reduction in the availability of attention towards input from other modalities. Therefore, this hypothesis suggests that if a person's attention is directed to visual information, there is a bias towards that modality to the detriment of others, such as touch.

The 'distraction' theme suggested that the visual information in some cases was engaging enough to take attention away from the task, which according to the directed-attention hypothesis (Posner et al., 1976), may have had consequences for the perception of haptic feedback during the intervention. The directed-attention hypothesis (Posner et al., 1976) suggests that when attention is directed to visual information, attention is less focused on information from other modalities such as touch. Using this system, visuals were the first sensory modality the students experienced, and if the visual stimuli were as engaging as the 'distraction' theme suggests, then it is possible that more attention would be focused on the visuals than the subsequent haptics. If less attention was given to the haptic feedback, then the proposed benefits of using the haptic processing channel may have been diminished. It could therefore be possible that the lack of a significant effect of haptics on the increase in cell knowledge found in the ANOVA could, in part, be due to less attention paid to the haptic feedback in this study.

Visual dominance may also explain the lack of expected higher learning gains between haptic and non-haptic groups in the topic of diffusion and the concentration gradient. The concentration gradient is a topic that is especially suited for the use of haptic feedback (in the form of the forces acting on the molecules across a concentration gradient) for increased understanding (Section 2.4.5), and therefore, it was theorised that haptic feedback for this task may help increase understanding. The results however did not reflect this. According to the modality-appropriateness hypothesis (Welch & Warren, 1980), attention is directed according to which sense can provide the most accurate information, and so for learning about the concentration gradient in this task, attention should be directed towards the haptic sense. However, the directed-attention hypothesis suggests that if a person's attention is directed to visual information, there is a bias towards that modality resulting in decreased attention on other senses (such as touch). The students were exposed to visual information before the haptic feedback, and for previous tasks in the activity (grasping/moving/adding or removing molecules), visual information was likely most suitable for the students' needs. It is possible therefore, that being primed with visual information, coupled with a high amount of intrinsic cognitive load from the learning content and extraneous load from the presentation of the information, meant that the students' attention may not have been properly attuned to the haptic feedback provided.

In summary, the findings of the thematic analysis suggested that the visual information provided by the system was prominent, attention-grabbing and the most notable liked feature discussed by students. The students expressed that they enjoyed the visual aspects of the system, but the results of the quantitative analysis show that the haptic feedback (which was intended to be an impactful addition for those in the haptic group) did not yield a significant difference in learning gains. The prominence of the visual information and potential effects of visual dominance makes it possible that attention was drawn away from the haptic sense during the task. As the students' attention was first directed to visual information in the task, the directed-attention hypothesis (Posner et al.,

1976) suggests that a bias towards the visual modality may have been created, decreasing attention to the haptic sense. Additionally, unlike the concentration gradient topic, for many of the tasks involving haptics in the activity visual information may have been the most precise, which according to the modality-appropriateness hypothesis (Welch & Warren, 1980) may also reduce attention to the haptic sense.

5.4 Discussion chapter conclusions

The main study in this project aimed to answer the following research questions:

1. Will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?

2. Does existing spatial ability have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?

3. Does existing fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?

4. What design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?

Chapter 5 so far has discussed how these research questions were answered, the main findings of the quantitative and qualitative data analysis, and potential factors affecting the ability of the haptic feedback to aid learning in this study. This section will collate the discussion points and conclusions from this chapter including evidence from all sources of data, referring to the literature discussed in Chapter 2.

5.4.1 RQ1: Will haptic feedback enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment?

RQ1 aimed to determine whether haptic feedback can enhance learning of complex concepts in cell biology compared to no haptic feedback within the context of a collaborative, 3D learning environment. The literature review (Chapter 2) showed that although empirical evidence was mixed, there is theoretical justification for the beneficial effects of using haptics in the learning of abstract and complex biological concepts, such as those in cell biology.

However, according to the data analysis (Section 4.2), no significant benefits were found for the use of haptic feedback in learning compared to no haptic feedback (Section 4.2.5), either in the short term (pre to post-intervention) or longer term (pre-intervention to retention-test).

Potential explanations for why the findings of this study were contrary to what was expected according to theory included perception of haptic information, excess cognitive load, visual dominance, and user difficulties, which will be reviewed below.

5.4.1.1 Possible factors influencing the effect of haptic feedback

5.4.1.1.1 Perception of haptic feedback

As discussed in Section 4.3.1.1.1, findings from the thematic analysis showed that generally, those in the haptic condition had received haptic feedback and those in the and non-haptic condition did not (Sections 4.3.1.1.1 and 4.3.1.1.1.2). However, although students in the haptic condition experienced general haptic feedback according to the 'haptics' theme, there is some evidence that haptic feedback specific to the concentration gradient may not have been perceived prominently for many students. The true/false/unsure section analysis discussed in Section 5.2.2 showed that for questions relating to the concentration gradient, there seemed to be confusion on the topic for many students. Additionally, the 'concentration gradient' sub-theme from the thematic analysis showed that, although most students who discussed the concentration gradient haptic feedback came from the haptic condition, the number of items of data coded to this theme was relatively low, which suggests that many students may not have perceived the concentration gradient haptic feedback, or that it was not prominent enough to comment on.

The literature suggested the concentration gradient may be a topic for which haptic feedback may be particularly helpful, (Zacharia, 2015), and therefore, if the haptic feedback concerning the concentration gradient was not perceived sufficiently, this may have affected the ability for the haptic condition to demonstrate increased learning gains in this study. This is supported by Embodied Cognition (Barsalou, 2008), which would suggest that if students did not perceive the haptic feedback regarding the concentration gradient as intended, the absence of this experience for some students may have reduced the opportunities to create embodied experiences in the haptic condition. It is possible therefore, that the haptic condition may not have provided enough additional embodied experiences during the intervention to demonstrate the beneficial effects of haptic feedback.

Visual dominance may provide an explanation for why the haptic feedback regarding the concentration gradient may not have been perceived as strongly as intended, which is discussed in more detail in Section 5.4.1.1.3.

5.4.1.1.2 Cognitive load

CLT (Sweller, 1994) suggests that whilst learning, cognitive load has the potential to overload the working memory and hinder the processing of information. A discussed in Section 5.2.1.1, the topic used in this study provided high intrinsic cognitive load, as cell biology is known to be complex and difficult to understand. Extraneous cognitive load is provided by the way the information is presented and was increased by a novel learning environment with several interacting elements. The VR environment being new to the students required them to navigate with an unfamiliar interface, as well as answer questions and collaborate with their co-pilot during the task, taking up further working memory resources. Additional extraneous load may have also been provided by difficulties in using the system, which were identified in the thematic analysis and included technical problems, thimble issues, task difficulty, difficulty grasping particles and space restriction. Although the interruptions did not seem to influence the students' ability to complete the activity worksheet, it is possible that restarting the program may have interrupted the activity, making the task more difficult. Germane load can be increased if an activity is enjoyable and motivating (Van Merriënboer & Sweller, 2005), as students may be more likely to allocate working memory resources to their activities. There is evidence for increased germane load from the thematic analysis, which suggested that students enjoyed the activity, with the 'praise for the system' and 'preference for interaction' themes providing comments regarding enjoyment and engagement and a preference for the interactive learning experience. Together, intrinsic, extraneous, and germane cognitive loads combine to form the overall cognitive load, which in excess is detrimental to learning and has the potential to diminish any beneficial effects of using an additional haptic processing channel.

Cognitive load is relevant to both haptic and non-haptic conditions in this study, as both experienced the intrinsic cognitive load supplied by the learning material and extraneous load supplied by using a novel VR learning environment. Germane load was supplied to both conditions by the interesting, novel, technological and interactive aspects of the system. Although, findings from the thematic analysis suggested that non-haptic students expressed more motivating factors in the interviews, as demonstrated in themes such as ‘liked features’ (Section 4.3.1.2.2), ‘novelty’ (Section 4.3.1.2.3), and ‘praise for the system’ (Section 4.3.1.2.1). The haptic condition also experienced the additional extraneous load provided by the processing of haptic feedback in addition to the visual information experienced by both conditions. Additionally, the presence of haptic feedback may have increased extraneous load further for those in the haptic condition, as according to the ‘difficulties’ theme from the thematic analysis (Section 4.3.1.1.5), students in the haptic condition reported more difficulties using the system overall. More specifically, haptic students reported more difficulties with the thimbles of the haptic device, which from observation were sometimes seen to disconnect from the students’ fingers, often with influence from the vibrations accompanying the haptic feedback which were absent in the non-haptic condition.

Design decisions were made to reduce cognitive load, such as using the haptic modality as an additional processing channel, using collaboration during the task and using multi-fingered physical manipulation (Section 5.3.1.2.1), but evidence from the thematic analysis suggested that additional sources of cognitive load may have overloaded the working memory of some students, despite the use of haptic feedback (Section 5.3.1.1).

5.4.1.1.3 Visual dominance

Another factor which may have affected the ability of haptic feedback to aid learning in this study was the effect of visual dominance, which describes how when presented with multiple modalities, the visual sense has been shown to dominate (Posner et al., 1976). The modality-appropriateness hypothesis (Welch & Warren, 1980) suggests that when presented with incongruent information from multiple senses, the sense which allows the greatest precision is favoured. Vision is usually the most appropriate sense and is therefore favoured most often (Pye, 2008). As discussed in Section 2.4.3, particularly for the concentration gradient topic, haptic feedback may be able to provide information which is difficult to convey with visuals alone, and therefore according to the modality-appropriateness hypothesis, would be favoured as the most precise source of information. However, according to the ‘concentration gradient’ theme from the thematic analysis and the true/false/unsure section analysis, students may not have perceived the concentration gradient haptic feedback as strongly as intended (Section 5.4.1.1.1). Should this be the case, haptic feedback would not have been the most precise sense, with visual information providing the most accurate information during the task. In this situation, visuals may have been favoured according to the modality-appropriateness hypothesis (Welch & Warren, 1980), producing a visual dominance effect.

Additionally, the directed-attention hypothesis (Posner et al., 1976) suggests that if attention is directed to visual information, there is a bias towards that modality. Therefore, it is possible that more attention was focused on the visuals than the subsequent haptic feedback for this study, dampening the proposed benefits of using the haptic processing channel. The ‘seeing’ and ‘visualisation’ sub-themes from the thematic analysis showed that students enjoyed the visual aspects of the intervention and the ‘distraction’ theme showed that visual aspects were attention-grabbing. Additionally, it has been suggested that when visual information is adequate for the task, attention may not be attuned to haptic exploration due to its high processing cost relative to its benefits (Klatzky et al., 1991). It is possible therefore, that being primed with visual information coupled with a high amount of intrinsic cognitive load from the learning content and extraneous load from the presentation of information, meant that the students’ attention may not have been properly attuned to the haptic feedback provided.

5.4.1.1.4 User difficulties

The thematic analysis (Section 4.3.1) revealed some instances of difficulties in the use of the haptic system which may have affected the ability of the haptic feedback to aid learning in this study. The 'difficulties' theme from the thematic analysis identified some issues in using the system, such as grasping particles. Grasping particles within the model was discussed as difficult in most interviews, and so it is possible that some students may not have grasped molecules securely whilst moving them across the membrane and therefore did not perceive the concentration gradient haptic feedback as intended. These difficulties in using the system may have also increased the amount of extraneous cognitive load on the students' working memory, as discussed in Sections 5.2.1.3.1 and 5.3.1.1.1.

Additionally, it is possible that some students may not have fully understood the questions being asked of them during the activity. Evidence for this comes from the 'task difficulty' sub-theme identified in the thematic analysis, which showed that some students had some difficulty with the task, with some commenting that they would have preferred more detailed instructions. Also, there were more items of data present in the 'task difficulty' theme from students in the haptic condition than the non-haptic condition (29 haptic, 9 non-haptic), suggesting that students in the haptic condition may have found the task more difficult. This could be because they were exposed to additional haptic feedback during the task, increasing the amount of information to be processed and therefore the cognitive load of the task. If more haptic students were confused by the worksheet, this may have had an effect on the results of this study. However, the task was not so difficult as to stop students from completing (Appendix RR) or enjoying (Section 4.3.1.2.1) the activity, suggesting that difficulties were not overly detrimental to their experience.

5.4.2 RQ2 and RQ3: Does existing spatial ability/fine dexterity have an impact on the ability of students to learn from haptic feedback provided within a collaborative, 3D learning environment?

RQ2 and RQ3 aimed to determine whether existing spatial ability or fine dexterity influenced how students learned from the intervention. These research questions were answered using ANCOVAs, which allowed spatial ability and fine dexterity to be controlled for during statistical analysis (Section 4.2.6).

The analysis showed that spatial ability did not have a significant influence on the students' learning. However, fine dexterity (specifically finger fine dexterity) was shown to significantly affect the ability of students to retain their knowledge between post-intervention and retention time points. A negative correlation was found between the difference in score between post-intervention and retention-tests and the finger fine dexterity scores, suggesting that those with lower finger fine dexterity tended to retain more of their cell knowledge than those with higher dexterity scores.

Fine dexterity was chosen as a variable that may affect the ability of students to learn from the intervention, as the use of a multi-fingered haptic system required manipulation of objects using the thumb and index finger. It was thought that lower fine dexterity had the potential to complicate manipulation within the VR environment, and therefore low fine dexterity had the potential to negatively affect learning. Therefore, the finding that fine dexterity had a negative relationship with retention of knowledge was counter to expectations.

CLT (Sweller, 1994) would suggest that difficulties using the system would exert extraneous cognitive load, which in excess can be a detriment to the processing of information. However, the findings of RQ3 suggest that those with lower fine dexterity were not negatively affected by any related difficulty in using the system, and so any extraneous cognitive load from using the system experienced by those specifically with lower fine dexterity was not significantly detrimental.

It is possible that those with lower fine dexterity spent more time moving the molecules within the model than those with higher fine dexterity, which may have resulted in more exposure to experiences during the task which could be embodied, which according to Embodied Cognition (Barsalou, 2008) can create cognitive anchors for understanding abstract concepts (Reiner, 2009). The potential for creating embodied experiences has been shown to also be important for increased learning (Han, 2013; Zacharia & Olympiou, 2011), and therefore it is possible that if students spent longer interacting and had more chances to create embodied experiences during the task, they may have retained more knowledge. Additionally, if lower fine dexterity had slowed down the activity for some students, this may have resulted in increased thinking or collaboration. However, as students had received lessons in the topic of cell biology in the time between post-intervention and retention-tests, it is also possible that newly acquired knowledge may have affected the relationship between fine dexterity and retention in this study, and therefore this finding should be treated tentatively (discussed further in Section 5.7).

To answer RQ4, the data was further explored with qualitative methods, which were able to reveal factors that may have affected the role of haptics in learning for this study, including cognitive load, visual dominance, and user difficulties. These are discussed in the following section.

5.4.3 RQ4: What design decisions can be made to support the use of collaborative, 3D learning environments capable of providing haptic feedback for learning complex concepts in cell biology in schools?

In this study, design decisions were made with guidance from the literature to create an intervention capable of providing a collaborative, 3D learning environment capable of providing haptic feedback for learning complex biological concepts. Although in this study the haptic condition was not found to result in significantly different learning gains compared to the non-haptic condition, the literature review was able to inform features supported by theory that would help deliver a system which successfully delivered engaging VR content, resulting in learning gains for the sample overall. The thematic analysis was also able to identify features of the intervention that students found to be supportive or not supportive to their learning experience, and theory explored in the literature review was used to explain why these features may have supported or not supported the learning of complex biological concepts. Evidence for design decisions that can be made to support the use of learning environment capable of providing haptic feedback for learning complex concepts in biology are discussed in the sections below.

5.4.3.1 Creating a motivating and enjoyable activity

As discussed in the literature review (Chapter 2), there is evidence that enjoyment of a task may make students more likely to invest in germane cognitive load for their learning (Van Merriënboer & Sweller, 2005). The theme ‘praise for the system’ was identified in the thematic analysis, documenting expressed enjoyment or interest using the system or completing the activity. This theme reoccurred repeatedly throughout the interviews and showed that students enjoyed using the system. The ‘liked features’ theme identified more specific features which the students expressed enjoying, including the visual aspects of the system, being able to move things, feeling in general and feeling forces specifically. By incorporating engaging visual information, integrated interactivity, and haptic information, an interesting, enjoyable system can be created, which according to the literature can result in increased germane cognitive load and deeper learning (Section 2.4.4).

5.4.3.2 Interactivity

The thematic analysis identified the theme ‘learning by discovering and interacting’ (Section 4.3.1.1.3.1), which showed that students felt that interacting with the system and exploring in VR allowed them to discover and learn during the activity. The sub-theme ‘preference for interaction/experiencing for themselves’ (Section 4.3.1.2.4.1) also found that students enjoyed taking ownership over their own learning, by observing and experiencing first-hand and learning directly compared to receiving information passively. It is possible that by taking ownership of their learning experience, students may be more likely to invest germane load to process the information (Vandewaetere & Clarebout, 2013) (Section 2.4.4,). The thematic analysis therefore suggests that a feature of the intervention that students felt they enjoyed and that benefited their learning involved discovering and interacting. Additionally, as discussed in Section 2.4.3, TEL has been suggested to enable hypothesis testing in areas of science learning where direct manipulation of real-world objects is not possible (Rutten et al., 2012). A system that allows students to learn by interacting and discovering themselves may therefore allow students to test their own hypotheses and support their learning of complex concepts.

5.4.3.3 Collaboration

The intervention for this study was designed to incorporate collaborative learning, with a pilot and a co-pilot taking turns in their roles and working together on the task activity. As discussed in Section 3.3.2.2.1, head-mounted VR displays can promote strong feelings of presence in the virtual environment, however, this isolation can also diminish the auditory connection to the ‘outside’ world (McGill et al., 2015), limiting the ability for users wearing the head-mounted display to communicate with others. However, with the pilot and co-pilot arrangement in this study, only the pilot wore the head-mounted display, with the co-pilot present in the ‘outside world’ able to view and manipulate the virtual space through a desktop display. This arrangement was designed to facilitate collaboration during the task.

As discussed in Section 2.4.4.1.2, working collaboratively in this way is also a method of lowering cognitive load, as multiple learners are thought to have the potential to expand individual processing capacities during complex tasks by dividing cognitive load between co-operating working memories (F. Kirschner et al., 2009b; Laughlin et al., 2002; Laughlin et al., 2006). Additionally, interest and motivation (which as discussed in Section 2.4.4 may provide germane cognitive load) have been suggested to be improved in biology by allowing peer discussion through collaboration (Odom, 1995).

Evidence also suggests that collaboration is more beneficial for learning complex subjects compared to simple subjects, as the ‘transaction costs’ (working memory resources needed to collaborate between parties in comparison with the potential learning gains) are lower (Andersson & Rönnberg, 1995; F. Kirschner et al., 2009b; Meudell et al., 1992). Therefore, collaborative learning (such as the pilot/co-pilot system used in this study) should be beneficial for the learning of complex concepts such as those in this study. The benefits of collaboration are supported by the thematic analysis, which identified ‘learning collaboratively’ as a theme present in every interview (Section 4.3.1.1.2). All students responded that they enjoyed working collaboratively in the activity, with an overwhelming preference for collaborative over individual work on this task. The use of communication and discussion in making sense of the material and answering questions was identified by students as a reason for enjoying collaboration, suggesting that students felt collaboration was a supporting feature in their learning. Therefore, collaboration would likely be a positive aspect to incorporate when designing activities for 3D learning environments capable of providing haptic feedback for learning cell biology in schools.

5.4.3.4 System familiarisation

The ‘novelty’ theme identified in the thematic analysis (Section 4.3.1.2.3) showed that the system was often described as exciting, novel, and more memorable than usual methods of learning,. Excitement from a novel system may provide germane cognitive load, but this comes with the disadvantage of having to learn to navigate and use the learning environment during a time-limited activity. The literature suggests that a novel system may exert additional extraneous cognitive load on the student as they navigate how to use the system and make sense of information simultaneously (Sweller, 1994). Excess cognitive load has been identified as a potential factor in the lack of increased learning for the haptic condition, and therefore any lowering of extraneous cognitive load could be beneficial for learning. The use of collaboration and the intuitive multi-fingered design of the haptic system (Section 3.3) were design features which could lower extraneous cognitive load during the task, but more extensive familiarisation to make students more adept at using the system before the intervention would potentially lower extraneous cognitive load during the task.

The following sections of Chapter 5 will discuss contributions made to the research area, limitations, and recommendations for future research.

5.5 Contribution to Existing Knowledge

This thesis provides a significant contribution to the field of the use of haptics in science education. In this study, RQ1 determined whether there was a significant difference in learning between with the use of haptic feedback compared to no haptic feedback. Previous studies (discussed in Section 2.4.3) have compared haptic and non-haptic methods in the learning of science education. However, these studies did not address RQ2 or RQ3 by controlling for spatial ability and fine dexterity.

This study was also the first to compare haptic and non-haptic learning in science with a multi-fingered haptic device, which provided a more intuitive method of manipulation than Phantom Touch 3D, joystick or tracker-ball methods used in previous studies. It has been suggested that multi-fingered haptics is imperative for a truly immersive VR experience, and multi-finger haptic feedback is important for dexterous manipulation in virtual environments (Lee et al., 2019). Therefore, the successful implementation of multi-fingered haptics in this study is contributory to the development of haptic VR learning environments for complex biological concepts.

Evidence from the thematic analysis (Section 4.3.1) has also provided a contribution to knowledge. The thematic analysis provided in-depth insight into students' opinions on how the intervention supported or did not support their learning, and identified evidence of cognitive load and visual dominance, which offer explanations as to why the benefits of haptics may have been inhibited in this study. Previously discussed studies which also found no beneficial effect of haptic feedback (Section 2.4) had proposed the effects of cognitive load and visual dominance as possible influencing factors (Minogue & Jones, 2006; Wiebe et al., 2009). The thematic analysis in this study was able to provide evidence for these effects and corroborate cognitive load and visual dominance theories as valid concerns in the use of haptic VR systems in secondary school science learning.

There is also a methodological contribution in the use of appropriate tests of spatial ability and fine dexterity for haptic devices in secondary science education, such as those used in this study (Section 3.3.3.3). Interacting with a 3D virtual space requires the hand to be able to rotate and navigate, requiring hand dexterity, whether that be with a Phantom (stylus) or multi-fingered style haptic device. The Morrisby Fine Dexterity tweezer test was identified as an appropriate test in previous literature regarding the use of haptic devices in the medical training field (Shahriari-Rad, 2014). This test required participants to place as many metal collars and washers on a board of pins within a time limit, using both their fingers and a pair of tweezers. The Morrisby Fine Dexterity test had been used previously in a project using a Phantom Touch 3D haptic device (Shahriari-Rad, 2014), for which the tweezer section of the test was especially suited, as the grip and rotation used in manipulating tweezers is reminiscent of using a stylus. However, the Morrisby Fine Dexterity test also included a finger section, which involved fine manipulation using the thumb and finger in a pinching motion, which is similar to how students manipulate components of the VR model using the multi-fingered system. The finger fine dexterity scores from the Morrisby Fine Dexterity test was found to be a significant co-variate in this study, which suggests that this part of the test may be especially relevant for the use of multi-fingered haptic devices.

The 3D nature of the haptic space resulted in spatial ability also being identified as an important variable to be measured in this project. The SRT (Levy & Levy, 1999) consisting of the Spatial Views and Solid Figure Turning sub-tests, and the WAIS-III BDT subset measuring visuo-spatial ability and depth perception were identified as widely used measures of spatial ability appropriate for use in the HapTEL project (Shahriari-Rad, 2014). An aspect of spatial ability that seemed to be most pertinent to 3D models in cell biology was spatial visualisation (Huk, 2006; Vlaardingerbroek et al., 2014), which the BDT was characteristic of testing (Hegarty & Kozhevnikov, 1999). The Solid Figure Turning sub-test also measured functions of spatial visualisation, along with the Spatial Views sub-test. Spatial Views also involved spatial orientation, which had been referred to as a complimentary skill associated with the ability to use visualisation to create effective mental models in science learning (Barnea, 2000). As such, the BDT and Spatial Views and Solid Figure Turning sub-tests of the SRT were identified as appropriate for this study. However, the BDT from the WAIS-III was not suitable for use with the students used in this study due to their younger age. Therefore, the BDT from the WISC-IV (Wechsler, 2003) was used as a substitute to better suit the sample age group and was implemented successfully in this study.

Although the identification of the SRT, BDT and Morrisby Fine Dexterity tests as suitable for use with haptic devices was conducted previously during the HapTEL project (Shahriari-Rad, 2014), the adaption and use of these tests for children aged 12-13 in this study contributed to existing knowledge. Additionally, the piloting process and use of these tests as appropriate for a multi-finger haptic VR intervention contributed to the existing knowledge of psychometric tests related to the skills needed to interact with and learn from haptic, 3D cell models.

5.6 Implications

5.6.1 Reception of haptic interventions for learning cell biology

The quantitative analysis showed that, although students did not benefit significantly from haptic feedback compared to no haptic feedback, students in this study did learn from the system overall and retained their knowledge (Section4.2.5). The findings from the thematic analysis showed that, not only did students correctly perceive that they had increased their knowledge, but revealed a positive impression of the intervention, perceiving it as enjoyable and beneficial to learning. As seen in the thematic analysis' 'liked features' theme (Section 4.3.1.2.2), students expressed liking the intervention, with the most commonly discussed liked features being visual aspects and the ability to move objects, which were features present in both the haptic and non-haptic conditions. Students were also found to enjoy both feeling in general and feeling forces specifically. The 'feeling forces' sub-theme (Section 4.3.1.2.2.4) showed that some students commented specifically on liking features of feeling forces within the system, which was exclusive to the haptic condition. Therefore, although the haptic condition did not significantly increase knowledge scores compared to the non-haptic condition, from a total of 15 haptic interviews, either the 'feeling forces' or 'feeling in general' sub-themes (Section 4.3.1.2.2) were present in 9 (60%), suggesting that most haptic students' perceptions of the haptic experience were positive.

The 'liked features' (Section 4.3.1.2.2), 'preference for interaction/experiencing for themselves' (Section 4.3.1.2.4.1), and 'comparison to regular teaching' (Section 4.3.1.2.4) themes also suggested that, regardless of condition, students enjoyed that the intervention allowed them to take ownership over their own learning by observing, manipulating and experiencing learning content directly, compared to receiving information passively (discussed in Section 5.3.1.2.1.2). Positive student perceptions of the intervention are beneficial, as there is evidence that enjoyment of a task may make students more likely to invest working memory resources for their learning (Van Merriënboer & Sweller, 2005) (Section 5.3.1.1.2). As discussed in Section 5.3.1.1.2, the positive reception of this intervention therefore has implications for the implementation of 3D VR and haptic systems aimed at 12-13 year-old students, as this method of interaction has been shown by the thematic analysis to provide an interesting, enjoyable intervention for this age group, which according to CLT (Sweller, 1994) could increase the allocation of working memory resources to the learning activity.

5.6.2 The use of haptics in learning cell biology

Although students expressed positive opinions of the intervention regarding their learning (Section 5.4.3.1), students in the haptic condition did not benefit significantly compared to those in the non-haptic condition. CLT (Sweller, 1994) and visual dominance theories have been discussed as potential explanations for these findings (Section5.2.1.3).

CLT (Sweller, 1994) suggests that whilst learning, cognitive load can reach a level that can overload the working memory, which could be detrimental to learning regardless of the use of an additional haptic processing channel. Evidence from the thematic analysis suggests that there were possible sources of excess cognitive load present in the task (Section 5.3.1.1), which may have affected the findings of this study. Although intrinsic load comes from the topic to be learned and germane load is associated with engaging and motivating tasks, extraneous cognitive load comes from the way information is presented, which can be reduced with instructional design, consequently lowering the overall cognitive load provided to students. The findings of this study suggest that cognitive load and visual dominance may inhibit the effect of using haptics in learning complex biological concepts, and therefore, an implication is that effects of excess cognitive load should be considered whilst designing haptic interventions and tasks, with a focus on lowering extraneous cognitive load to allow for optimum conditions for any beneficial effects of haptic feedback on learning to occur. Recommendations for the reduction of the effects of cognitive load were discussed in Section 5.3.1.2.1.

Visual dominance was also suggested to have potentially affected the results of this study. Visual dominance describes how the visual sense can dominate others when presented with multiple modalities (Posner et al., 1976), and how if attention is directed to the visual sense, a bias to that sense can be created. There is evidence from the thematic analysis that the visual aspects of the system were a prominent feature for students, and that the concentration gradient haptic feedback may not have been perceived as strongly as intended, which together may have resulted in visual dominance. As haptic information was thought to be the most beneficial to topics where visual information is inadequate (Zacharia, 2015) (such as the concentration gradient), a possible visual dominance effect for that topic would be detrimental to the ability for haptics to benefit learning. Like the effect of cognitive load, an implication is that visual dominance should be considered in the design and implementation of haptic systems for learning. Recommendations for the reduction of the effect of visual dominance are discussed in Section5.6.5.3.

5.6.3 The effect of fine dexterity on retention of knowledge

A finding from this study was that finger dexterity significantly affected the ability of students to retain their knowledge between post-intervention and retention test time points, suggesting that on average, those with lower finger dexterity tended to retain more of their knowledge than those with higher finger dexterity.

As discussed in Section 5.2.3.2, a possible explanation for the effect of fine dexterity on retention of knowledge is that those with lower fine dexterity may have spent more time moving the molecules within the model than those with higher fine dexterity. Spending more time moving and feeling objects in the model creates more opportunities for embodied experiences, which can help create multimodal representations (Barsalou, 2008) and can create cognitive anchors for understanding abstract concepts (Reiner, 2009). Additionally, if lower fine dexterity had slowed down the activity for some students this may have resulted in increased thinking or collaboration, as there would have been more time to discuss and consider the learning content. Therefore, it is possible that if students have more chances to create embodied experiences or have more discussion and thinking time during the task, they may retain more of their knowledge. We know from observations during the study that there were differences in how students interacted with the model. For example, some students spent time grasping and moving molecules, whereas others were more forceful in their approach or preferred to move molecules by pushing or hitting them. Therefore, there may have been some differences in the opportunities for students to create embodied experiences depending on how students chose to interact with the system.

The theory that fine dexterity might have influenced how the students interacted with the model, influencing opportunities for embodied experiences or discussion could be tested by analysing the video data to determine how students used their time in the activity and compare differences between those of different fine dexterity abilities. Recommendations for further research on this topic is discussed in Section5.8.

An implication of the finding that fine dexterity has a significant effect on the retention of knowledge is that fine dexterity may be an existing skill to be considered during the design of haptic VR interventions and in future investigations into their use in schools. These findings suggest that it may be beneficial to further explore the differences in how students interact with the system and how fine dexterity may affect student interactions with haptic VR systems such as the one used in this study.

5.6.4 Design implications for the use of haptic systems in science education

5.6.4.1 Use of collaboration

The design of the intervention and how it was presented to the students was piloted extensively (Section 3.3), and consequently key design features were observed in the main study to be conducive to the students' use of the system. For example, a key design feature for the implementation of the intervention in this study was the use of collaboration. For this study, the students were paired together, with each taking the role of 'pilot' and 'co-pilot' for half of the activity. The pilot could interact and manipulate the virtual world in VR using the head-mounted display (Oculus Rift), whilst the co-pilot could observe the VR world through a computer screen, manipulate the scale of the virtual objects and switch between the phases of the task by using key commands. This configuration allowed students to collaborate whilst completing the task, and was supported by the literature, which suggested that allowing peer discussion, time to hypothesise and using a variety of teaching methods in classrooms could benefit engagement and motivation (Odom, 1995) and foster deep learning (Moreno et al., 2001). Additionally, working collaboratively was a method of lowering cognitive load, as multiple learners are thought to have the potential to expand individual processing capacities during complex tasks by dividing the cognitive load between co-operating working memories (F. Kirschner et al., 2009b; Laughlin et al., 2002; Laughlin et al., 2006). Therefore, collaboration was thought to be a beneficial feature to include in the design of the haptic intervention in this study.

Additionally, the pilot/co-pilot method allowed collaboration despite the isolating effect of the head-mounted display. The thematic analysis provided evidence for the successful use of a pilot/co-pilot arrangement in this study, as shown in the 'learning collaboratively' theme (Section 4.3.1.1.2), which showed that all students stated that they enjoyed working collaboratively in the task. Therefore, the pilot/co-pilot method for the use of haptic VR interventions was shown to be successful in facilitating effective use of the haptic device and collaboration between students in this study. An implication is that this study provides evidence that collaboration using the pilot/co-pilot method was positively received by students and conducive to learning, and therefore may be implemented in future intervention designs to facilitate more effective learning with VR systems.

5.6.4.2 Difficulties in grasping

Another design implication comes from the apparent difficulty of some students in grabbing and moving particles within the model. The ‘grasping particles’ sub-theme (Section 4.3.1.1.5.4) showed that grasping molecules was discussed as difficult in 22/31 interviews. The haptic device in this study used a multi-fingered manipulation method that allowed students to grasp and move things in the model using the thumb and forefinger in a pinching motion, and observationally students seemed to adapt to the multi-fingered controls quite quickly. Additionally, although difficulties in grasping particles was mentioned by several students in the interviews, those difficulties were not detrimental enough to dampen the students’ enjoyment of the activity (as shown in the ‘praise for the system’ theme, Section 4.3.1.2.1), prevent the completion the task (Appendix RR), or stop the sample from learning during the intervention overall (Section4.2.5). These factors therefore suggest that grasping particles may have been challenging enough for students to mention in their interviews, but not markedly detrimental to their experience with the learning environment. Challenges in grasping particles, therefore, may be due to the novelty of the system, which has the potential to introduce excess extraneous cognitive load (Section 5.4.3.4). Therefore, a period of familiarisation may be necessary for students to become more adept with the environment before using it as a learning exercise in the classroom. Implications therefore include that the use of a multi-fingered haptic device was shown to be successful in facilitating intuitive interaction with the VR model, but the difficulties some students found in grasping molecules suggest that a period of repeated familiarisation using the system before undertaking a learning experience may be beneficial.

5.6.5 Recommendations for the use of haptic VR systems in classrooms

Findings of this study have been collated in this section to inform on recommended features to implement in the use of haptic VR systems, which may be beneficial to their implementation in the classroom. Recommendations discussed here come from the literature review, observations from the main study and the thematic analysis, which are considered together to form recommendations for the successful implementation of haptic VR environments in the classroom.

5.6.5.1 Collaboration

This study used a method of interaction for the haptic VR intervention which was found to be successful in facilitating collaborative learning and was a positive feature identified in student interviews. As discussed in Section 3.4.6, a pilot/co-pilot method was used for the activity in this study, where students worked in pairs with each taking the role of 'pilot' and the other 'co-pilot' for half of the activity. Using this method, students were encouraged to collaborate during the task and were able to explore and discuss the learning content throughout.

All students who took part in this study stated that they enjoyed working collaboratively in this task, as shown in the 'learning collaboratively' theme (Section 4.3.1.1.2), where students expressed their appreciation of the ability to communicate and discuss during the activity. The 'roles as pilot and co-pilot' theme also showed that the use of the pilot/co-pilot method provided a grounding influence for some pilots, making them feel more connected to the real world. As discussed in Section 3.3.2.2.1, head-mounted displays can promote strong feelings of presence in the virtual environment, but can limit communication (L. Chan & Minamizawa, 2017; McGill et al., 2015). However, with the pilot/co-pilot arrangement in this study, the grounding effect of the co-pilot seemed to allow pilots to stay more connected to the real world. The finding from the thematic analysis that students enjoyed collaboration and the finding from the ANOVA which showed that students learned successfully from using the system (Section 4.2.5) would suggest that this method of collaboration was successful.

The literature also supports the use of collaboration in complex tasks, as allowing peer discussion, and time to hypothesise has been suggested to benefit engagement, motivation and deep learning (Moreno et al., 2001; Odom, 1995). Working collaboratively was also a method of lowering cognitive load, as multiple learners are thought to have the potential to expand individual processing capacities during complex tasks by dividing the cognitive load between being co-operating working memories (F. Kirschner et al., 2009b; Laughlin et al., 2002; Laughlin et al., 2006). The literature would suggest that collaboration would be beneficial for increased understanding of complex biological topics by increasing discussion and lowering cognitive load. Therefore, collaboration in the form of a pilot/co-pilot partnership (described in Section 3.3.3.5.1.7) is recommended to be a useful feature in the use of haptic VR interventions for learning in secondary science education.

5.6.5.2 Multi-fingered haptics

A multi-fingered method of interaction was used for the main study in this project, which was chosen over the Phantom Touch 3D stylus after considering the findings of Pilot 3 (Section 3.3.4). In Pilot 3, it was shown that participants seemed to manipulate more intuitively using the multi-finger device, rated the multi-contact interface as having a lower subjective workload, showed more agility with the multi-fingered device and there was a lack of significant difference in completion time between the two devices. The findings of Pilot study 3 therefore suggested that multi-fingered haptics were more appropriate than the Phantom Touch 3D used previously. The literature supported the use of multi-figured haptics for use with a haptic VR model, as it has been suggested that multi-fingered haptics is imperative for truly immersive VR experience, and is important for dexterous manipulation in virtual environments (discussed previously in Section 3.3.4.1) (Lee et al., 2019).

Although the thematic analysis and observations by researchers showed that some students had problems grasping the particles in the model (Section 5.3.1.1.1.2), Pilot 3 had shown that the multi-fingered system resulted in increased agility in comparison to the Phantom Touch 3D device, as well as being the preferred method of interaction for participants. Therefore, it is likely that despite some challenges, the multi-fingered haptic device is the most suitable for manipulating objects within a virtual model such as the one used in this study.

Overall, the literature suggests that multi-fingered haptics is the preferred method of manipulation in virtual environments (Lee et al., 2019), and Pilot 3 showed that our particular multi-fingered device was preferable to the more widely used Phantom stylus-based device. Therefore, it is recommended that a multi-fingered device is used for manipulation in haptic VR environments for intuitive movement and increased immersion.

5.6.5.3 Directing attention to haptic feedback

As discussed in Section 5.2.1.3, a factor which could have affected the ability of the haptic feedback to result in larger learning gains was that students may have had problems perceiving the haptic feedback regarding the concentration gradient across the membrane, as the ‘concentration gradient’ sub-theme showed that most students in the haptic condition did not discuss the forces across the concentration gradient. The directed-attention hypothesis (Posner et al., 1976) suggests that if attention is directed to visual information (as the 'liked features' theme from the thematic analysis would suggest, see Sections 4.3.1.2.2.1 and 5.3.1.3) there is a bias towards that modality, and therefore it is possible that more attention was focused on the visuals than the haptic feedback regarding the concentration gradient, dampening the perception of the haptic sense. The directed-attention hypothesis (Posner et al., 1976) therefore suggests that, when introducing a student to a 3D haptic VR intervention, attention should be directed to the haptic feedback foremost to avoid visual dominance effects. This could be accomplished by increasing the strength of the haptic force across the membrane in addition to introducing the haptic feedback as the focus at the beginning of the activity and referring to the haptic feedback available to the student during the task. Keeping focus on the haptic feedback during the task could be part of the role of the teacher should a haptic VR system be used in classrooms, which is discussed further in Section5.6.5.4.

5.6.5.4 Teachers role in the use of haptic systems

This study aimed to develop an exploratory learning aid which could be used in a classroom setting. As such, the study was designed with the consultation of teachers and with consideration for the curriculum. Originally, it was discussed within the project group that a VR learning environment capable of providing haptic feedback such as the one designed for this study would be used as one tool amongst several to help students increase their understanding of cell biology, possibly being used in a circus of activities in a cell biology lesson. This study however deliberately took the learning environment outside of the traditional classroom setting so that data collection could take place, although it did take place in the school science laboratories and over the course of a single lesson. As such, the role of the researchers was to inform the students of essential instructions and direct the student to follow the worksheet so that they could explore and learn without intervention (except during technical difficulties). A researcher protocol was used to ensure that each pair of students was exposed to the same information

(Appendix Q), but this limited the amount of interaction between researcher and student during the activity. In comparison, should the activity be used in a classroom setting, the role of the teacher would be important for addressing some issues that were identified in this study. The role of the teacher would add structure to the activity and therefore could ensure that students were focused on the haptic feedback during the activity. As discussed in Section5.6.5.3, the directed-attention hypothesis (Posner et al., 1976) suggests that when introducing a student to a 3D haptic VR intervention, attention should be directed to the haptic feedback foremost to avoid visual dominance effects. The role of the teacher in a classroom setting could keep focus on the haptic feedback and promote discussion on what the student can feel.

Additionally, the role of the teacher may be advantageous for the collaboration between students whilst using haptic systems. As discussed in Section 2.4.4.1.2, collaboration has the potential to lower cognitive load on complex tasks (F. Kirschner et al., 2009a, 2009b; Laughlin et al., 2002; Laughlin et al., 2006), and there is evidence that teachers can support collaboration by helping students focus on tasks and encouraging collaborative skills such as explaining, justifying, negotiating and giving feedback (Hennessy et al., 2005).

The ‘task difficulty’ sub-theme from the thematic analysis (Section 4.3.1.1.5.3) also identified that some students had difficulty with the task and that they would have preferred more detailed instructions. The presence of a teacher during the activity would also allow students some support in the task should they require it, and as task difficulty was identified as a possible source of extraneous cognitive load, teacher support during the task may help lower cognitive load.

The analysis of true/false/unsure section of the cell knowledge test also found that students may not have understood moving through levels of magnification (Section 5.2.2.7.2), which was identified in the literature review as a topic with widespread misconceptions (Section 2.1.2.1.1). Statement 10 referred to the nature of the model in relation to the cell membrane and was implemented to determine whether students grasped that the model was a small part of the membrane overall. However, the answer changes from pre-intervention to post-intervention suggested that there was confusion over the nature of the model in relation to the cell membrane and that some students may not have fully understood that the section of membrane from the model was a small part of a larger whole. The worksheet used a cell diagram to express that the model was a small section of the larger cell, but the findings from Statement 10 would suggest that this was not sufficient for some students. Comparatively, in a classroom setting with a teacher to frame the activity, the students would not be reliant on a worksheet or diagram to understand the context of the model. Including the framing of the activity in the role of the teacher would therefore facilitate better understanding of this aspect of the activity.

The role of the teacher in the implementation of 3D learning environments capable of providing haptic feedback in the classroom therefore, may allow a more focused and structured activity, allowing for focused discussion and attention given to what haptic feedback the students may feel, and additional context given to the activity with the use of complimentary classroom activities.

5.7 Limitations

To answer the research questions of this study, a pragmatic paradigm was used (Section 3.2.1), informed by previous literature, theoretical justification, user requirements and technological considerations. However, throughout the development, testing and analysis of this study some limitations became apparent which should be taken into consideration whilst interpreting the findings and contribution.

Firstly, a limitation of this study may involve the selectivity of the partner schools who took part in this project. Both schools were independent, academically selective schools, and therefore students who attend these schools may not represent the typical student population. Students attending selective schools generally have been shown to outperform those from non-selective schools academically (Smith-Woolley et al., 2018), and consequently, the students used in this study were likely not of typical academic ability. Consequently, the students in this sample were unlikely to be representative of the academic ability spread of the wider population. Nevertheless, analysis of the data (Section 4.2) showed good variance and normal distribution of cell knowledge, spatial ability and fine dexterity scores, suggesting that there were a good range of abilities present in the sample. Therefore, although the students were not likely typical in their academic abilities, they provided a range of data representing a variety of capabilities.

A further limitation to this study was that during the main study and subsequent analysis, evidence emerged that some students may not have perceived the haptic feedback as intended. Grasping molecules within the model was discussed as difficult in most interviews, and so it is possible that some students may not have grasped molecules securely, causing them to not perceive the haptic feedback regarding the concentration gradient as intended. The ‘concentration gradient’ sub-theme revealed in the thematic analysis showed that most students in the haptic condition did not discuss the forces across the concentration gradient, which may suggest that they did not perceive the relevant haptic feedback, or at least they did not find it pertinent enough to discuss. As discussed in Section 5.2.1.1, if students did not perceive the haptic feedback regarding the concentration gradient (for which the literature suggests haptic information should be particularly useful for), according to Embodied Cognition (Barsalou, 2008) it is possible that the differences in embodied experiences between the haptic and non-haptic conditions were not substantial enough to affect the results. The duration of the learning intervention is also relevant. During the intervention, each student spent 15 minutes as the pilot and therefore had a limited amount of time in which to experience the haptic feedback. Limited exposure to the haptic feedback may have also affected the ability for students to create embodied experiences, and therefore experience the benefits of the haptic condition on their learning.

There are also potential limitations regarding the retention interval in this study. As discussed in Section 5.2.3.2, working with schools within term-time resulted in an eight-month gap between post and retention-tests. Typically, a retention interval is around 2-4 weeks (Anderson, Hecker, Krigolson, & Jamniczky, 2018; Nungester & Duchastel, 1982; Reynolds & Glaser, 1964; Ricci, Salas, & Cannon-Bowers, 1996) and therefore eight months between engaging with the intervention and re-taking the test of knowledge is an extended period of time, which may have affected the retention scores of the students. Additionally, due to the extended retention period, students had received lessons in the topic of cell biology between post-intervention and retention-test time points. This is a limitation of this study, as the measurement of the retention of knowledge (and consequently the effect of fine dexterity on the retention of knowledge) may have been compromised by factors outside of the intervention. Regular curriculum learning may have altered the student’s knowledge of cell biology and therefore any findings in relation to retention of cell knowledge should be treated with caution.

A potential limitation to consider in this study was the design of the assessment. As this study took place within a larger research project (Section 1.2), the assessment was designed with additional considerations, such as identifying additional learning opportunities during the intervention, teachers' expectations of the intervention and their students' capabilities, and the requirement for a more general assessment of learning. Therefore, the design of the assessment was influenced by the research aims and considerations of the project team as a whole, rather than being solely based on the theoretical rationale for the use of haptic feedback discussed in this thesis. Nevertheless, as I was involved in the collaborative design of the assessment, the test of cell knowledge was also designed to consider the research aims of this study. Additionally, although the assessment included some items that were more relevant to the aims of the project group as a whole, this thesis has focused on the items most relevant to the aims of this study and to the research questions (as discussed in Sections 3.4.8.5, 4.3.1 and 5.2.2.4). Therefore, it is likely that the collaborative design of the assessment had an insignificant impact on the findings of this research.

As discussed in Section 4.2.8, the collaborative working arrangement used in the intervention along with individual testing presents a limitation for this study. The design of the assessment was that each student was tested on their cell knowledge at pre-intervention, post-intervention and at retention. However, the working arrangement during the intervention was collaborative, with dyads working together on the activity. The independence-of-observations ANOVA assumption can be violated when individual-level data is collected from more than one person from the same dyad (O'Connor, 2004), and although ANOVA is considered as a robust statistical test generally tolerant against violations of assumptions, the violation of the assumption of independence-of-observations can lead to a loss of robustness (Kenny & Judd, 1986). As shown in Section 4.2.8, ICCs show that although the dyads in which students worked did not significantly affect student's change in knowledge score from pre to post-test, the independence-of-observations assumption was violated for the change in knowledge score post to retention-test, suggesting that who the students worked with during the intervention had an influence on their retention of knowledge. As discussed previously however, the long retention interval is a limiting factor, and therefore findings related to retention should be treated with caution.

Finally, an additional limitation of this study concerns the rationale for the activity design. This study was conducted as part of a larger research project, but the theoretical rationale of this study and that of the research project overall were not identical. Consequently, the activity design was not based solely on the theoretical rationale discussed in this thesis, but also on the research aims and concerns of the research group as a whole. The activity design therefore included additional practical considerations such as timetable constraints, school curriculum, teachers' expectations of the system and of their student's abilities, and the intention to support collaborative learning. However, as an active participant in the activity design, my research into the literature discussed in Chapter 2 had a direct influence on development. Consequently, although there were constraints on the design of the activity, many of the additional considerations provided positive attributes to the intervention. For example, collaborative working was found to be a beneficial feature for students (Section 4.3.1.1.2), and the classroom setting allowed an examination of the design implications for the use of haptic learning environments in schools (Section 5.6.5), and the role of teachers in their successful implementation (Section 5.6.5.4). Therefore, although the activity design was a collaborative endeavour, my guidance during development ensured that the activity was conducive to the research aims of this study.

5.8 Recommendations for further research

The limitations of this study discussed in Section 5.7 elicited suggestions for further research in this topic to explore the research questions in more depth. Additionally, further lines of enquiry have emerged from the research process which could be explored in further research. This section will discuss recommendations for further research based on both the limitations identified in this study and the opportunities for further exploration which had emerged through the exploration of the research questions.

Firstly, a recommendation for further research would be to expand the sample population to different academic abilities and include non-selective schools to achieve a more representative sample. The typical difference of abilities in students from selective and non-selective schools presents an opportunity to explore whether academic ability influences how students interact with haptic systems whilst learning.

In Section 5.7, it was discussed that the duration of the learning intervention was a potential limitation of this study, as each student spent only 15 minutes as the pilot experiencing haptic feedback. Embodied Cognition (Barsalou, 2008) suggests that limited exposure to haptic feedback may affect the ability for students to create embodied experiences, and therefore limit the ability of students to experience the benefits of the haptic condition on their learning. Therefore, a recommendation for further research would be to increase the duration of the exposure to haptic feedback to explore how the increased potential for creating embodied experiences may affect the efficacy of haptic feedback in learning.

As discussed in Section 5.4.1.1.1, there was some evidence that students may not have perceived the haptic feedback as intended, in part due to difficulties in grasping particles. In further research therefore, more comprehensive familiarisation of the system may improve the grasping and movement of the particles and more accurately reflect the effects of haptic feedback in the model. Additionally, designing a worksheet to stress the importance of grasping molecules before moving them across the membrane may be beneficial, as well as bringing more attention to important haptic feedback they may perceive. As discussed in Section 5.6.5.4, the role of the teacher in the implementation of the system to a classroom setting may address some of these concerns, as the presence of a teacher can bring focus on the haptic feedback students may feel and encourage constructive ways to interact with the system to optimise the potential for embodied experiences. A recommendation for further research would also be to create a more focused study on the concentration gradient across the membrane, focusing on a more pronounced haptic force across the membrane to allow students to focus fully on this complex concept for which haptic information may be especially beneficial. Focusing the task on the concentration gradient may help prevent visual distractions and dominance of the visual sense that may have affected the perception of haptic feedback in this study and could allow a better measurement of the effect of haptic feedback on learning.

After investigating the effect of haptic feedback on learning gains in cell biology in this study, several new avenues of enquiry emerged which could be considered for future research. Firstly, it was suggested in Section 5.2.3.2 that those with lower fine dexterity may have spent more time moving the molecules within the model than those with higher fine dexterity, creating more opportunities for embodied experiences or discussion of the learning content. As discussed in Section 5.6.3, further research may explore this relationship in more detail by analysing the video data collected during this study. Using the video data, the time taken for students to move molecules and the time used in discussion of the learning topic could be measured and used to compare the interaction behaviour between those with high or low fine dexterity. Gestures used by students during the activity could also be analysed to determine opportunities for embodied learning to further test this hypothesis. Additionally, for further data collection, screen captures of the activity could be used to record students' activities using the system, which could be used identify differences in how students interact with the model more accurately than from video data.

Another recommendation for further research concerns the successful use of collaboration in this study and how to expand on the benefits collaboration can provide for learning with a haptic VR intervention. As discussed in Section 5.4.3.3, collaboration was a feature conducive to student learning in this study. Although the pilot/co-pilot configuration provided a grounding influence for the pilot and facilitated discussion, some students mentioned that the different views of the system (Oculus Rift versus monitor) created a barrier to their communication. Therefore, should a VR system be designed to allow multiple students to interact with the same model, interaction between pairs of students in the virtual world may provide an opportunity for more direct collaboration. Research could explore this concept further by comparing the dual display pilot/co-pilot partnership with an arrangement where both parties could view and collaborate in the same space.

5.9 Final Words

Overall, this study did not find a beneficial effect for the use of haptic feedback in the learning of complex, abstract biological concepts. Nevertheless, this study has been contributory to the development of the use of haptics for learning complex concepts in biology. By designing a collaborative, enjoyable, 3D haptic environment to facilitate exploration and hypothesis testing, identifying factors which may affect how students perceive and utilise haptic feedback, and exploring in-depth information on the students' perspectives on the use of haptics and their learning, this study has opened up several avenues research to further explore the potential role of haptics in science education. The literature suggests that under correct conditions, haptic feedback could provide an invaluable resource for the increased understanding of previously unobservable phenomena, and it is my hope that the findings of this study will be used to further explore how haptics can be used most effectively in the learning complex, abstract scientific concepts.

6 Reference

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7 Appendix

7.1 Appendix A: Table summarising my role in the research project.

As discussed in Section 1.2, this PhD resides in a larger project group, which consisted of several researchers and industry professionals who collaborated in the designing, development and testing with differing levels of involvement at varying points in the research. Appendix A summarises who was responsible for each task, whether that be me, another researcher in the project team, or completed collaboratively by the project group as a whole.

Table 42: Table summarising my role in the research project

Work Completed	Persons Responsible
• Initial project aims • General planning and aims for pilot tests • General design and direction decisions for cell model and haptic device development • Experimental design for main study • Testing including haptic activities, observations, and administration of some psychometric tests in pilot studies. • Conducting semi-structured interviews • Design of cell knowledge test structure	Project group as a whole
• Generation of research questions Literature Review • Defining the research paradigm • Timetables and organisation with schools for Pilot tests	Myself

• Timetables and organisation with schools for Main Study • Selection of psychometric and psychometric tests used in pilot and main study testing • Production of materials for psychometric tests and administration in main study • Creation and administration of ethics documents for pilot and main studies (including collecting consent and providing information) • Ethics applications for pilot studies (2,4 and 5) and the main study. • Data entry and organisation including creation of Excel/SPSS databases • Anonymisation of data • Proofreading of transcriptions (provided by transcription service). • Analysis (quantitative and qualitative) of pilot and main study results. • Writing of thesis	
• Conduction of focus group in Pilot 5	Supervisor and I (KCL)
• Selection of software and hardware used for haptic device • Programming and implementation of haptics	Bioengineering researchers (University of Reading)

• Creation of Google feedback forms • Marking of short answer questions in knowledge test • Ethics for Pilots 1 and 3 including information and consent sheets	
• Generation of cell model	Gaia 3D
• Biological expertise including model development and knowledge test questions • Creation of cell knowledge test questions • Creation of marking rubric for short answer questions in cell knowledge test	Biology researchers (University of Reading) and education researchers (my supervisor, KCL).
• Initial recruitment of students in school • Advice on curriculum	Science teachers of partner schools

7.2 Appendix B: Ethics approval for Pilot 1

University of Reading

Prof Simon C Andrews
School of Biological Sciences

Chair of SBS Research Ethics Committee
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Reading RG6 6AJ

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12th April 2016

RE: 3D Haptic Learning – Study 1: Interacting with Cells
Systems Engineering: Prof. William Harwin, Dr. Faustina Hwang, Dr. Ozan Tokatli
Biological Sciences: Dr. Natasha Barrett, Dr. Chris Jones.

Dear Applicants

The above ethics project submission has been reviewed by two members of the SBS Ethics Committee and is considered **suitable for acceptance.** Your submission has now been passed on to the Head of School for his approval. A summary of the views of the committee is below:

'Information for the Ethics Committee': this document is fine, thank you. *However, on p. 1, 3 lines up, you may wish to alter 'other members' to 'other academic members', so that the students know that other student volunteers will not be informed concerning how they got on with the equipment.*

'Information Sheet for Participants': also fine, thanks again.

'Questionnaires': fine also

Sincerely

SC Andrews

7.3 Appendix C: Information sheet for Pilot 1

Information Sheet

Project Title: 3D Haptic Learning – Study 1: Interacting with Cells

What is the purpose of this study?

We are developing a system that uses 3D virtual reality and haptics (i.e. virtual touch) to teach science. The aim is to enable students to manipulate and interact with objects in 3D, either individually or in small groups, in order to better support learning. The project is a collaboration between the University of Reading's, School of Systems Engineering, King's College Department of Education and Professional Studies, Abingdon School, and The Abbey School. The project is funded by the Leverhulme Trust. For this particular study, we would like to get user feedback on an initial prototype of the system, in order that we can improve it.

Why have I been invited to participate?

We are inviting undergraduate students who are studying cell biology to participate.

What will I be asked to do?

We will ask you to attend a session in pairs. One person will view a 3D model of a cell on a virtual reality headset, and the other will view the same cell on a computer screen. Each person will have their own controls for interacting with the system.

We will ask you to work together as a pair to complete a series of tasks with the cell model, for example, selecting a part of a cell, manipulating it, and answering some questions about it.

Afterwards, we will ask you for feedback about the system (e.g. what you liked or disliked, or what could be improved), through an interview and a questionnaire. The questionnaire will also ask for information about your age, gender, handedness, and experience with 3D systems. The entire session should take approximately 1 hour of your time.

What data will be collected, and how will it be used?

As you interact with the system, we will take notes about how you interact, and which aspects of the system worked well and which not so well. We will also take notes of your interview responses and collect your completed questionnaire. With your permission, we will also video record the session for later analysis and for sharing with other members of the project team. The data collected in this study will be used to help us improve our system design and may be published.

Will my data be kept anonymous?

You will be asked to provide your name and contact details, and to sign a consent form so that the University can keep a record of your participation in the study. However, data from the study will be stored, processed, and reported using anonymous user IDs.

The audio and video recordings will also be saved using anonymous user IDs. It is possible that you could be identified from the contents of the recordings, however, these recordings will be used only for data analysis by the research team and will not be shared without your explicit consent.

Where will the studies take place?

The study will take place in the School of Systems Engineering at the University of Reading Whiteknights campus. The researchers will contact you to provide further details of where you will need to go, and to arrange a time slot for you.

What if I do not wish to complete the study?

Participation is entirely voluntary, and you can withdraw at any time without giving a reason. Whether or not you choose to participate will have no direct bearing on your module grade.

Can I learn the results of the study?

If you would like to learn the results at the end of the study, please contact the researchers.

Who are the researchers responsible for this study?

This study is being conducted by the School of Systems Engineering and the School of Biological Sciences.

Systems Engineering:

Prof. William Harwin, Professor, w.s.harwin@reading.ac.uk, x0 118 378 6792

Dr. Faustina Hwang, Associate Professor, f.hwang@reading.ac.uk, 0 118 378 7668

Dr. Ozan Tokatli, Postdoctoral researcher, o.tokatli@reading.ac.uk

Biological Sciences:

Dr. Natasha Barrett, Teaching Fellow, n.e.barrett@reading.ac.uk, 0 118 378 7022

Dr. Chris Jones, Senior Research Fellow, c.i.jones@reading.ac.uk, 0 118 378 4429

Please feel free to contact us if you have questions.

This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.

7.4 Appendix D: Consent form for Pilot 1

Consent Form

1. I have read and had explained to me by ……………………………………………..…

   the accompanying Information Sheet relating to the project on:

   “3D Haptic Learning – Study 1: Interacting with Cells”

2. I have had explained to me the purposes of the project and what will be required of me, and any questions I have had have been answered to my satisfaction. I agree to the arrangements described in the Information Sheet in so far as they relate to my participation.

3. I understand that participation is entirely voluntary and that I have the right to withdraw from the project any time, and that this will be without detriment.

4. Either

   ☐ I agree to the interview/session being **video and audio** recorded.

   OR

   ☐ I DO NOT agree to the interview/session being **video and audio** recorded.

5. If you agree to the interview/session being **video and audio** recorded:

   I agree for the video and/or audio to be used in presentations and publications.

   ☐ WITHOUT anonymisation.

   ☐ if my face is anonymized (e.g. blurred out).

   OR

   ☐ I DO NOT agree for the video and/or audio to be used in presentations nor publications.

6. This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.

7. I have received a copy of this Consent Form and of the accompanying Information Sheet.

Name: ……………………………………………

Signed: ……………………………………………..

Date: ………/………/………

7.5 Appendix E: Notes taken by researchers from Pilot 1

Notes on educational issues from Haptics trial with Reading University biology students 200416

(N.B. This is my interpretation based on observations and discussions after the meeting and focused on educational considerations – not technical issues although there may be some overlap).

1. Confusion over cell wall/cell membrane – first pair needed help from tutor as to which was on the outside. Using an animal cell will change this and avoid confusion.
2. Cell organelles – most were able to identify chloroplasts, endoplasmic reticulum (some needed prompting from tutor regarding rough and smooth – N.B. ribosomes not present), Golgi, vacuole, nucleus. Peroxisomes – generally required prompting from tutor. Nucleolus – usually prompted from tutor.
3. Colour of structures. Most realised colour was not realistic although one student in first pair said, "I didn't think Golgi was green". In most cases tutor explained -very little real colour in cells except chloroplasts.
4. Large variation in students' capabilities in interacting with the 3D structure. This may have been affected by how they zoomed in – i.e. by moving the pen device or by using keyboard shortcut. Idea of a pre-activity to get used to the hardware and interaction good – need some thinking about what activity appropriate. Needs to rehearse all the possible useful actions – particularly: moving around an object to observe it from different angles, rotating the object, selecting object, dragging.
5. The size of the cursor was a distraction. The cursor was regarded as a cursor and not as a probe. Lab script referred to it as a grey sphere and talks about it colliding with a virtual object.
6. Some students seemed much more enthusiastic about the activity than others although all were engaged. And none rated experience less than good.
7. The way students collaborated varied between pairs as did the discussion. Probably need to design collaboration into the activity.
8. Phase 1 lab script – useful to see cells within tissue so they know where cell comes from. This task might be improved by making them take a screenshot from a different angle.
9. moving to Phase 2 should perhaps involve clicking and dragging the cell out from the other cells so that the background is not confusing.

10. Phase 2 – while the lab script focuses on investigating inside the cell, all 3 pairs did this by pulling the cell apart rather than probing into the cell and enlarging. They were then encouraged by tutors to rebuild the cell. Perhaps this deconstructing and constructing is a more useful educational exercise than the probing that was previously envisaged? In this trial it was encouraged by the way the software worked.
11. Most pairs responded mainly to tutor prompts rather than following the lab script. Need to consider the extent to which we want teacher interaction. This prompting appeared to be necessary/useful.
12. Most students thought this looked significantly different from textbook images – in particular – commented:
    a. Golgi looked different – they were used to cross-sectional view and did not articulate without prompting that the difference was due to the 3-D. One student said that in her head she pictured it as 2D and tend to forget cells are 3-D
    b. Much more messy.
    c. Perception of distance interesting

13. visual/haptic. Most were mainly focusing on the visual when they said it was cool etc. One student commented that they could feel it.
14. Phase 3 – most pairs found difficulty rotating the nucleolus to see the code. But they did appear to like this as a kind of game effect.
15. How to design the lab activities to encourage thinking about function? Some students appeared to be thinking about function (e.g. transport) when they were deciding where to position the objects.

7.6 Appendix F: Worksheet for Pilot 1

Interacting with a Virtual Plant Cell

In this lab you will be interacting with a virtual plant cell. You can touch, manipulate, and investigate the virtual cell using a haptic robot which is depicted below.

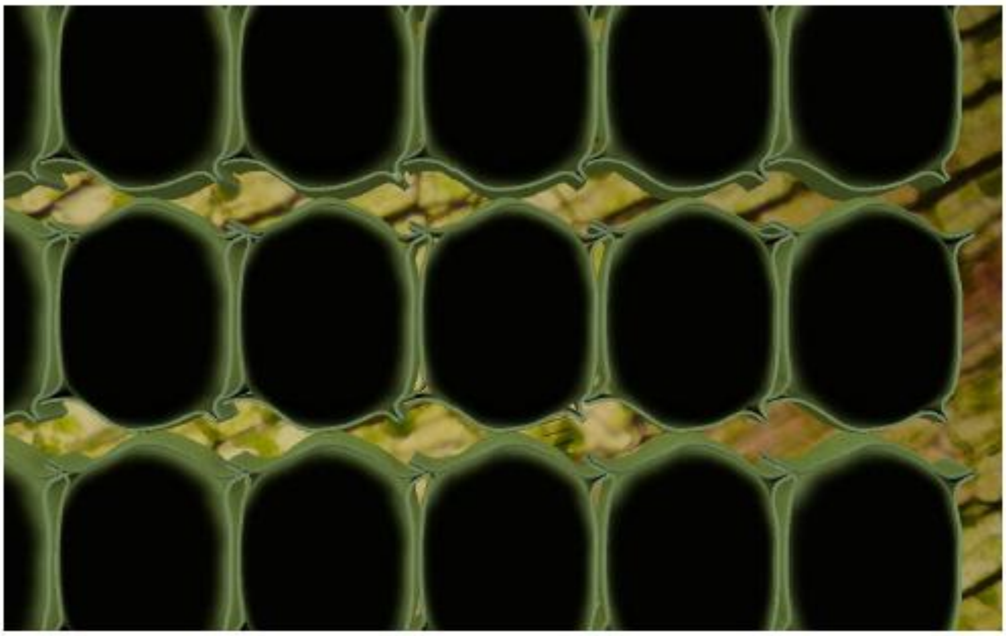
A **virtual world** is displayed on the screen, created by the computer and includes a plant cell model.

The **haptic device** is a robot which enables the user to physically interact with the virtual environment. As shown in the figure above, you have to hold the robot like you are holding a pen. As you move the robot, you control the movement of a grey sphere in the virtual world.

When the haptic device, i.e. the grey sphere in the virtual world, collides with a virtual object, a reaction force is calculated by the computer and this reaction force is applied to you through the haptic device.

Phase 1: Multiple Cells

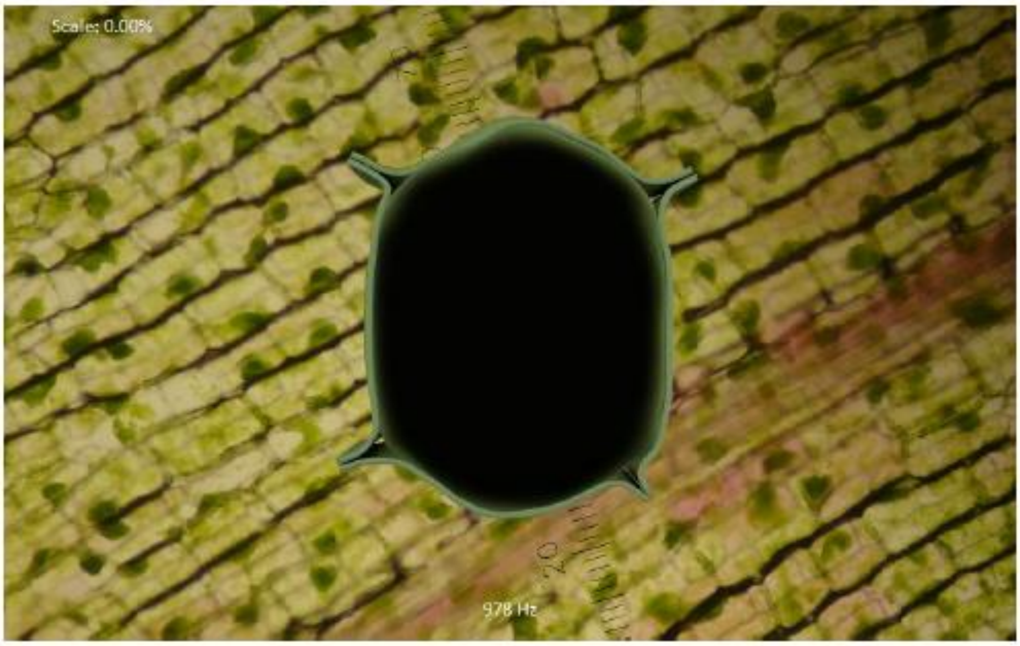
In this phase multiple plant cells are displayed in the virtual world and you can interact with and manipulate the cells using the haptic device.



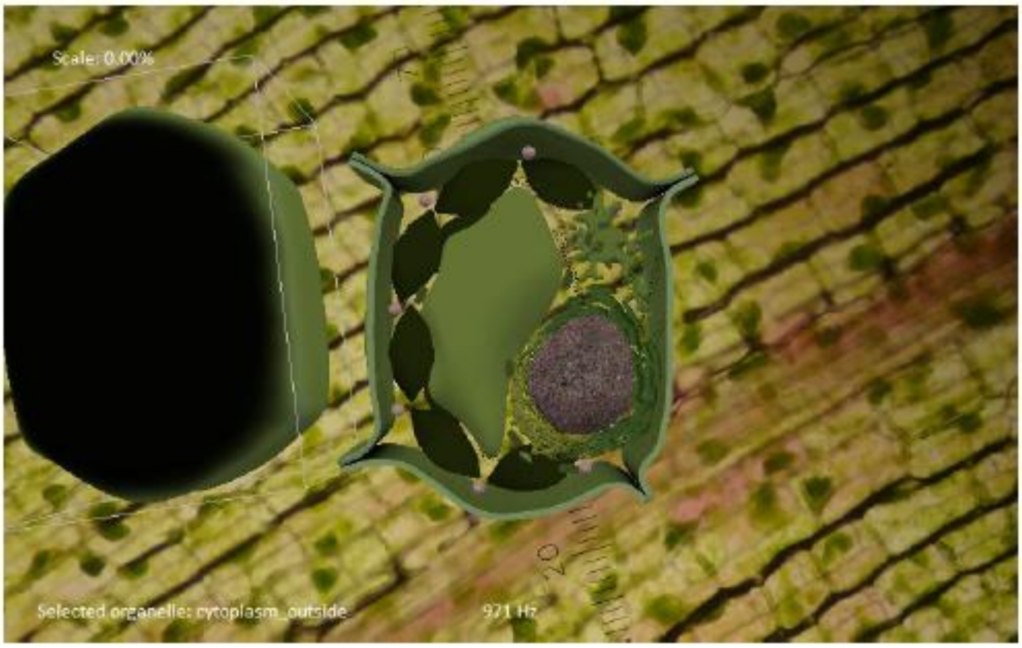
- You can look at the cells from different angles. Try rotating the cells using the **haptic device** and also by **clicking and dragging the mouse**.
- Select a cell and press **SPACE** to switch to *Phase 2: Single cell*.

Phase 2: Single Cell

In the second phase a single virtual plant cell model is displayed in the virtual world.



- First you have to remove the cell membrane/wall to see the interior of the cell. You can make the cell membrane transparent by selecting it and pressing **3** or you can grab the cell membrane/wall and take it away. In order to grab an object, first touch the object you want to grab and, while you are in contact press **BUTTON1** of the haptic device, while pressing the device, move the haptic device and observe that the virtual object is following your motion.



- After the cell membrane/wall is removed, investigate the interior of the cell. Try examining an object more closely by using the haptic device to bring it closer and by zooming in using one of the keyboard shortcuts.
- Identify the organelles. If you have difficulty in recalling the organelles, you can turn on the label by pressing **I**. The labels are displayed on the lower left corner of the window.
- Select the nucleus of the cell and press **SPACE** to switch to *Phase 3: Single Organelle*.

Questions

1. What are the things differ from the standard textbook diagrams?
2. How would you describe the number of mitochondrions available in the virtual cell?
3. What are your observations on the golgi in the virtual cell?
4. Which of the following organelle is missing in the virtual cell?
5. Do you think there is an organelle in the virtual cell which should not be available in a plant cell? If so, please name it.

Phase 3: Single Organelle

In the third and final phase, a single organelle is displayed in the virtual world and your aim is to investigate this organelle and reveal the DNA sequence hidden in the nucleus.

- A DNA sequence is hidden inside the nucleus. Please use any necessary functionality to reveal the code.
- Rotate the nucleolus until the DNA code is facing you and the letters are the right way up.
- After you finish the task please follow the link and fill in the form.

Questions

1. What is the DNA sequence coded on the nucleolus?

Keyboard Shortcuts

SPACE	Switch between phases
ESC	Quit the application
1	Increase transparency of the selected object
2	Decrease transparency of the selected object
3	Zoom in to the selected object
4	Zoom out from the selected object
s	Take a screenshot of the current view
l	Turn on/off the labels
#	Recenter the view

7.7 Appendix G: Online feedback questionnaire for Pilot 1

3D Learning with Haptics

* Required

About you

1. **Date** *

Example: December 15, 2012

2. **User ID** *

3. **Were you viewing the cell model primarily**

Mark only one oval.

- ( ) using the VR headset
- ( ) on the computer screen

4. **What year were you born?** *

5. **Gender** *

Mark only one oval.

- ( ) Female
- ( ) Male

6. **Preferred hand** *

Mark only one oval.

- ( ) Right-handed
- ( ) Left-handed
- ( ) Either

7. **How would you describe your experience interacting with 3D systems (tick all that apply)?** *

Check all that apply.

- [ ] This is my first time interacting with a 3D computer system.
- [ ] I have tried them once or twice before, but not used them extensively.
- [ ] I have tried them more than once or twice before, but not used them extensively.
- [ ] I frequently interact with 3D systems (e.g. computer gaming).
- [ ] I frequently interact with immersive virtual-reality systems.

About using the 3d learning system

How would you rate the ease of doing the following?

8. **Selecting objects**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

9. **Positioning objects**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

10. **Zooming/changing scale**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

11. **Achieving a desired viewpoint**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

12. **Knowing where you are in the model**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

13. **Coordinating the task with your partner**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

14. **Overall, I would rate the usability of this system as**
Mark only one oval.

- ◯ Worst imaginable
- ◯ Awful
- ◯ Poor
- ◯ OK
- ◯ Good
- ◯ Excellent
- ◯ Best imaginable

15. What are 3 things that you like about the system and why? *

16. What are 3 things that you would change about the system and why? *

About using the system to learn cell biology

17. What would you find useful about this system for learning cell biology? Please give specific examples. *

18. Does being able to "feel" the cell structures virtually help you learn better? Please explain. *

19. Does being able to move the cell structures help you learn better? Please explain. *

20. **If this system was available for general use, please tick all statements that describe how you think you would want to use it to support your learning (please tick all that apply)** *
Check all that apply.

- [ ] If this system was available for general use, please tick all statements that describe how you think you would want to use it to support your learning (please tick all that apply):
- [ ] I would want to use it to study in pairs or small groups.
- [ ] I would not want to use it at all.

21. **What would you like to see built into the system, that would make studying cells more interesting, fun, memorable, or effective for you?** *

7.8 Appendix H: System Usability Scale

System Usability Scale

	Strongly disagree 1	2	3	4	Strongly agree 5
1. I think that I would like to use this system frequently					
2. I found the system unnecessarily complex					
3. I thought the system was easy to use					
4. I think that I would need the support of a technical person to be able to use this system					
5. I found the various functions in this system were well integrated					
6. I thought there was too much inconsistency in this system					
7. I would imagine that most people would learn to use this system very quickly					
8. I found the system very cumbersome to use					
9. I felt very confident using the system					
10. I needed to learn a lot of things before I could get going with this system					

7.9 Appendix I: Online feedback questionnaire for Pilot 2

3D Learning with Haptics

* Required

About you

1. **Name** *

2. **What year were you born?** *

3. **Gender** *

Mark only one oval.

- ◯ Female
- ◯ Male

4. **Preferred hand** *

Mark only one oval.

- ◯ Right-handed
- ◯ Left-handed
- ◯ Either

5. **How would you describe your experience interacting with 3D systems (tick all that apply)?** *

Check all that apply.

- ☐ This is my first time interacting with a 3D computer system.
- ☐ I have tried them once or twice before, but not used them extensively.
- ☐ I have tried them more than once or twice before, but not used them extensively.
- ☐ I frequently interact with 3D systems (e.g. computer gaming).
- ☐ I frequently interact with immersive virtual-reality systems.

About using the 3d learning system

How would you rate the ease of doing the following?

6. **Selecting objects**

Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

7. **Positioning objects**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

8. **Zooming/changing scale**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

9. **Achieving a desired viewpoint**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

10. **Knowing where you are in the model**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

11. **Coordinating the task with your partner**
Mark only one oval.

	1	2	3	4	5	
Very hard	◯	◯	◯	◯	◯	Very easy

12. **Overall, I would rate the usability of this system as**
Mark only one oval.

◯ Worst imaginable
◯ Awful
◯ Poor
◯ OK
◯ Good
◯ Excellent
◯ Best imaginable

13. **What are 3 things that you like about the system and why? ***

14. **What are 3 things that you would change about the system and why? ***

System Usability Scale

On a scale of 1-5, how much do you agree with these statements? With 1 being strongly agree and 5 being strongly disagree.

15. **I think that I would like to use this system frequently ***
Mark only one oval.

	1	2	3	4	5	
Strongly agree	◯	◯	◯	◯	◯	Strongly disagree

16. **I found the system unnecessarily complex ***
Mark only one oval.

	1	2	3	4	5	
Strongly agree	◯	◯	◯	◯	◯	Strongly disagree

17. **I thought the system was easy to use ***
Mark only one oval.

	1	2	3	4	5	
Strongly agree	◯	◯	◯	◯	◯	Strongly disagree

18. **I think that I would need the support of a technical person to be able to use this system ***
Mark only one oval.

	1	2	3	4	5	
Strongly agree	◯	◯	◯	◯	◯	Strongly disagree

19. **I found the various functions in this system were well integrated** *
Mark only one oval.

	1	2	3	4	5	
Strongly agree	⬭	⬭	⬭	⬭	⬭	Strongly disagree

20. **I thought there was too much inconsistency in this system** *
Mark only one oval.

	1	2	3	4	5	
Strongly agree	⬭	⬭	⬭	⬭	⬭	Strongly disagree

21. **I would imagine that most people would learn to use this system very quickly** *
Mark only one oval.

	1	2	3	4	5	
Strongly agree	⬭	⬭	⬭	⬭	⬭	Strongly disagree

22. **I would imagine that most people would learn to use this system very quickly** *
Mark only one oval.

	1	2	3	4	5	
Strongly agree	⬭	⬭	⬭	⬭	⬭	Strongly disagree

23. **I felt very confident using the system** *
Mark only one oval.

	1	2	3	4	5	
Strongly agree	⬭	⬭	⬭	⬭	⬭	Strongly disagree

24. **I needed to learn a lot of things before I could get going with this system** *
Mark only one oval.

	1	2	3	4	5	
Strongly agree	⬭	⬭	⬭	⬭	⬭	Strongly disagree

About using the system to learn cell biology

25. **What would you find useful about this system for learning cell biology? Please give specific examples.** *

26. **Does being able to "feel" the cell structures virtually help you learn better? Please explain.** *

27. **Does being able to move the cell structures help you learn better? Please explain.** *

28. **If this system was available for general use, please tick all statements that describe how you think you would want to use it to support your learning (please tick all that apply)** *
Check all that apply.

- [ ] If this system was available for general use, please tick all statements that describe how you think you would want to use it to support your learning (please tick all that apply):
- [ ] I would want to use it to study in pairs or small groups.
- [ ] I would not want to use it at all.

29. **What would you like to see built into the system, that would make studying cells more interesting, fun, memorable, or effective for you?** *

About how much you have learned.

30. **On a scale of 0-9, how much did you learn in the lesson? With 0 meaning you learned nothing and 9 meaning you learned more than in any other lesson you've had.** *
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	
I learned nothing	○	○	○	○	○	○	○	○	○	○	I learned more than any other lesson I've had

31. **On the same scale, how much do you think you could have learned in the lesson had you had the ideal teacher?** *

Mark only one oval.

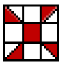
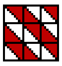
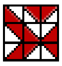
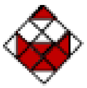
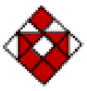
	0	1	2	3	4	5	6	7	8	9	
I learned nothing	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	I learned more than any other lesson I've had

7.10 Appendix J: Full WAIS-III BDT scoring sheet for Pilot 2

Block Design Test (BDT/WBDT)

Test Administrator Name:

Please note that the designs are drawn on your perspective.

	Design	Time Limit	Incorrect Design		Time (Secs)	Correct Design?		Score						
			Trial 1	Trial 2		(Please circle as appropriate)								
1		30"				Y	N	0	T2 1	T1 2				
2		30"				Y	N	0	T2 1	T1 2				
3		30"				Y	N	0	T2 1	T1 2				
4		30"				Y	N	0	T2 1	T1 2				
Start 5		60"				Y	N	0	T2 1	T1 2				
6		60"				Y	N	0	T2 1	T1 2				
7		60"				Y	N	0			16"-60" 4	11"-15" 5	6"-10" 6	1"-5" 7
8		60"				Y	N	0			16"-60" 4	11"-15" 5	6"-10" 6	1"-5" 7
9		60"				Y	N	0			21"-60" 4	16"-20" 5	11"-15" 6	1"-10" 7
10		120" (2:00 mins)				Y	N	0			66"-120" 4	26"-65" 5	21"-25" 6	1"-20" 7
11		120" (2:00 mins)				Y	N	0			66"-120" 4	46"-65" 5	31"-45" 6	1"-30" 7
12		120" (2:00 mins)				Y	N	0			76"-120" 4	56"-75" 5	41"-55" 6	1"-40" 7
13		120" (2:00 mins)				Y	N	0			76"-120" 4	56"-75" 5	41"-55" 6	1"-40" 7
14		120" (2:00 mins)				Y	N	0			66"-120" 4	46"-65" 5	36"-45" 6	1"-35" 7
		TOTAL SCORE IN EACH COLUMN												
									TOTAL RAW SCORE (MAXIMUM = 68)					

7.11 Appendix K: Spatial Relations Test for Pilot 2

Spatial Views

Name: ___________________

Directions:

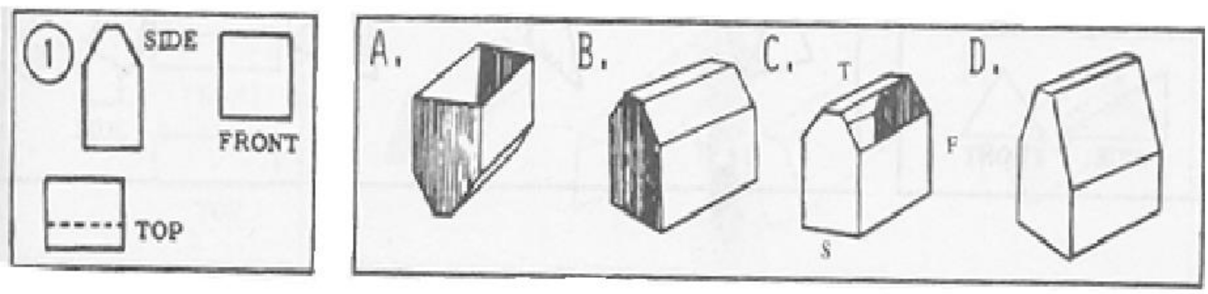
Each question in the following tests consists of a numbered picture showing top, front and side representations of a three-dimensional object.

DASHED LINES indicate FOLDS.

To the right of the numbered representations are four pictures, lettered A,B,C and D. You are to SELECT ONE OF THE PICTURES that would have the TOP, FRONT and SIDE representations shown in the numbered picture.

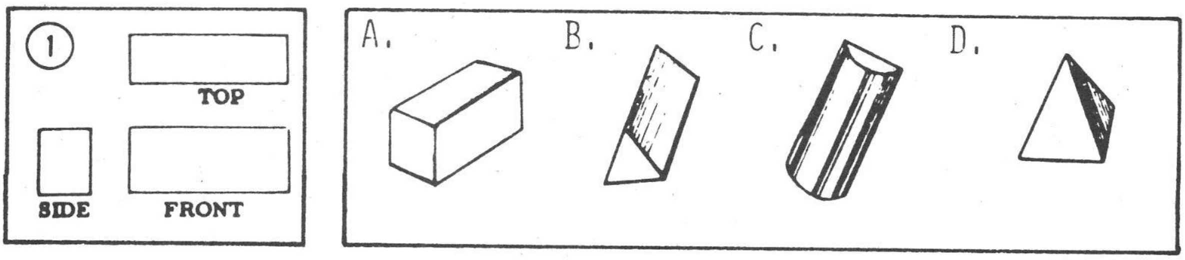
Please TICK the circle of your answer (A, B, C or D) beneath the question.

Example Question

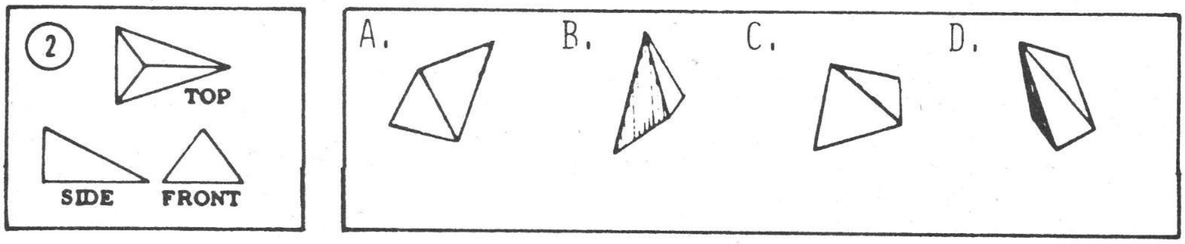


○ A ○ B ○ C ○ D

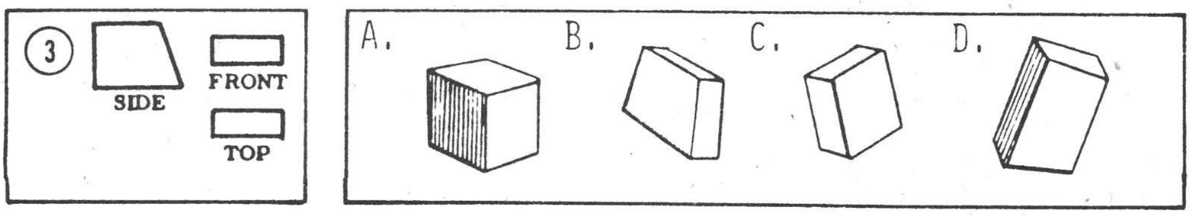
Test 1



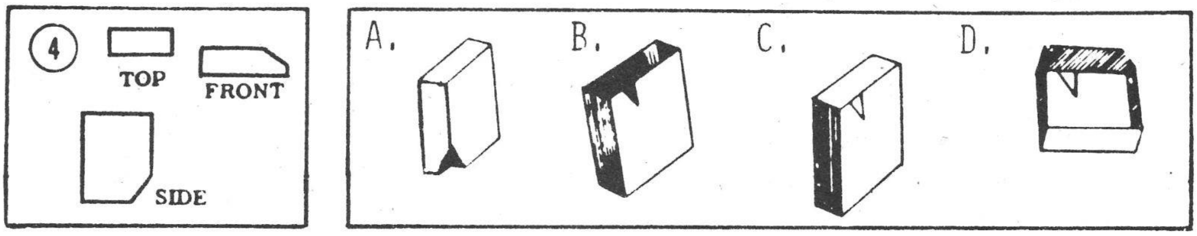
○ A ○ B ○ C ○ D



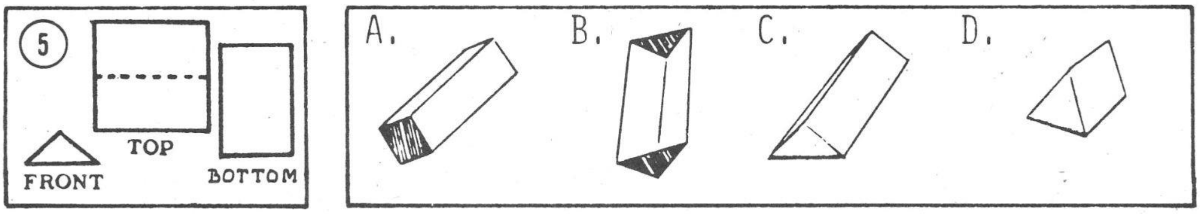
○ A ○ B ○ C ○ D



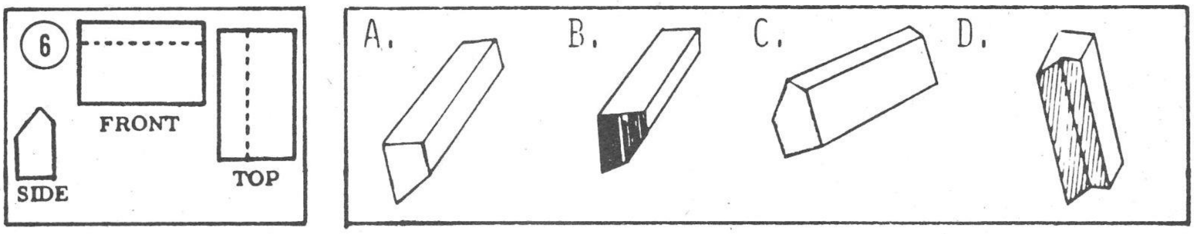
○ A ○ B ○ C ○ D



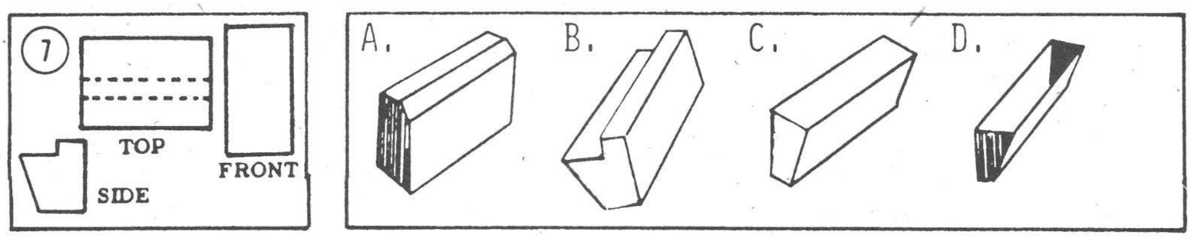
○ A ○ B ○ C ○ D



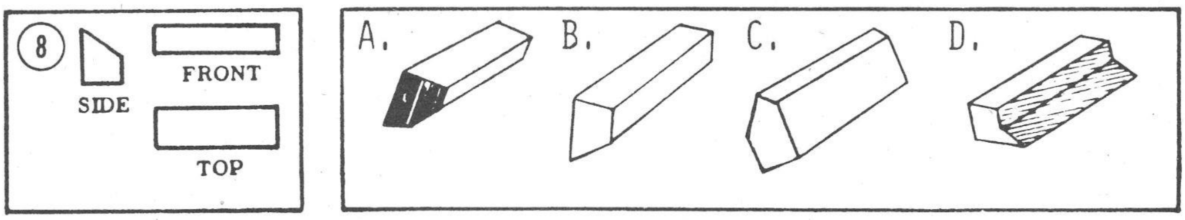
○ A ○ B ○ C ○ D



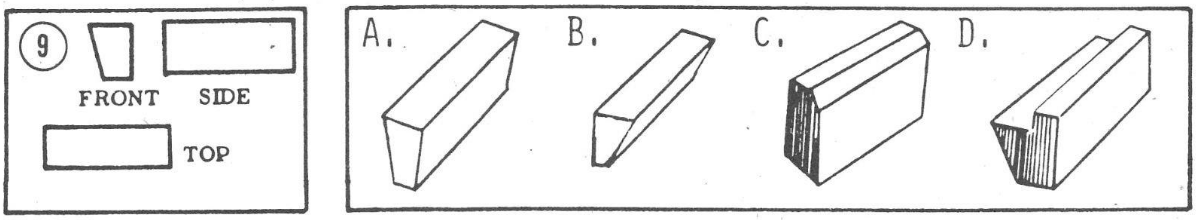
○ A ○ B ○ C ○ D



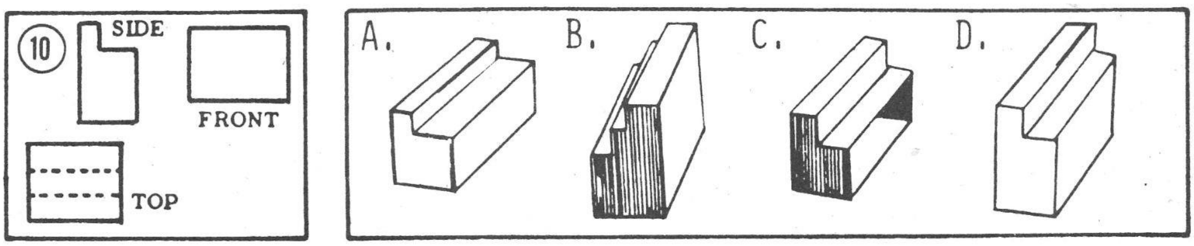
○ A ○ B ○ C ○ D



○ A ○ B ○ C ○ D

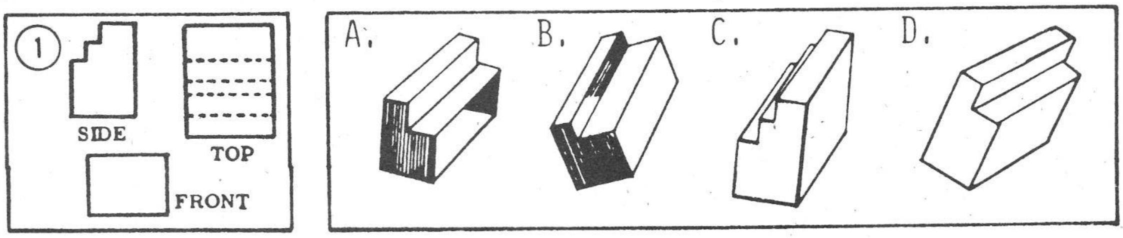


○ A ○ B ○ C ○ D

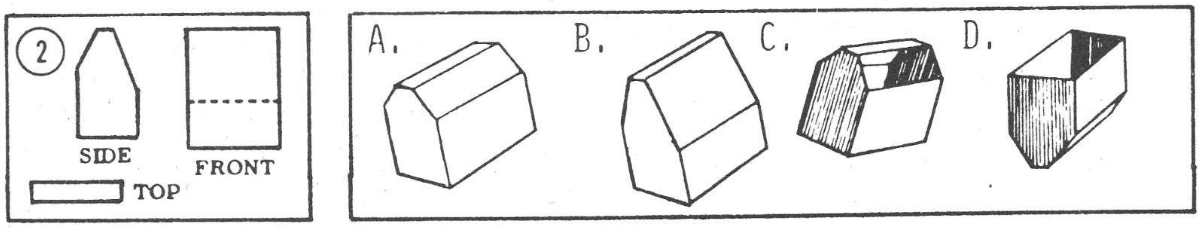


○ A ○ B ○ C ○ D

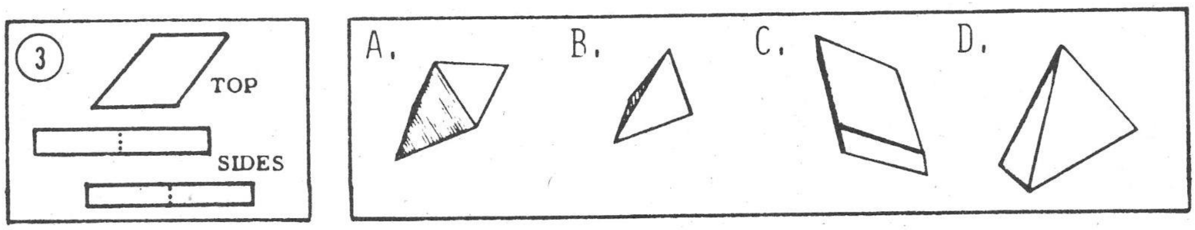
Test 2



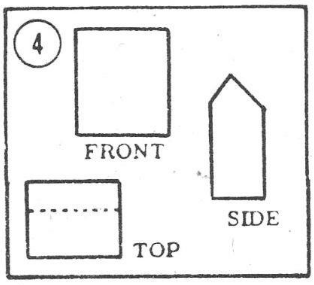
○ A ○ B ○ C ○ D

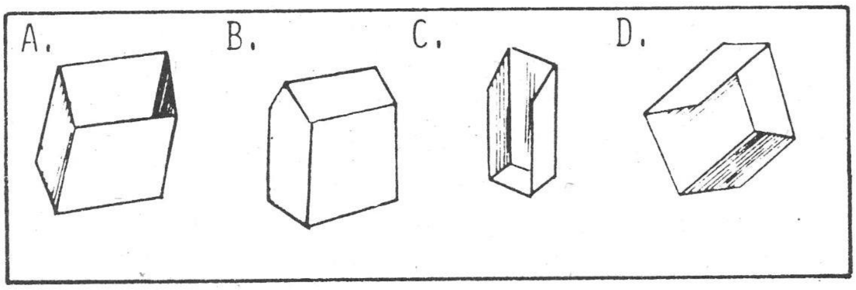


○ A ○ B ○ C ○ D

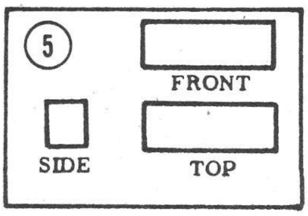


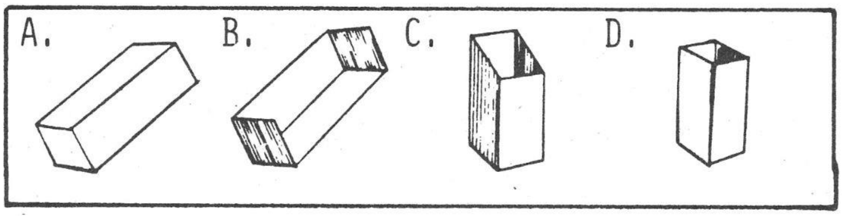
○ A ○ B ○ C ○ D



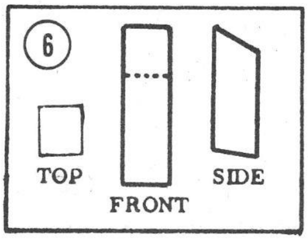


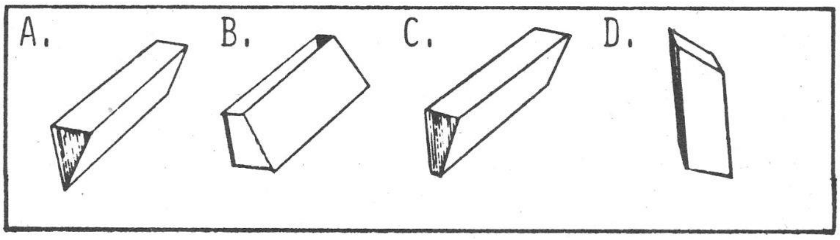
○ A ○ B ○ C ○ D



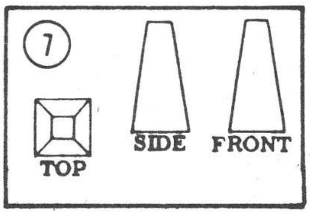


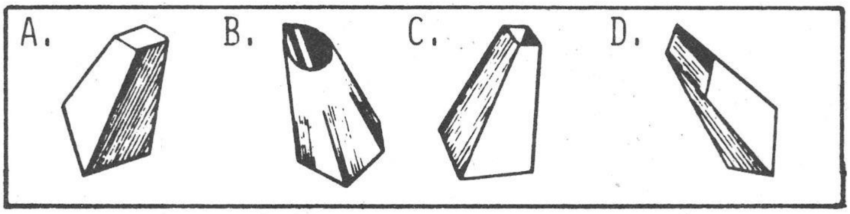
○ A ○ B ○ C ○ D



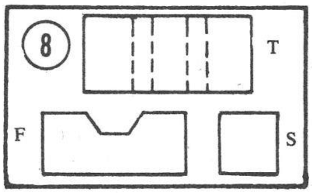


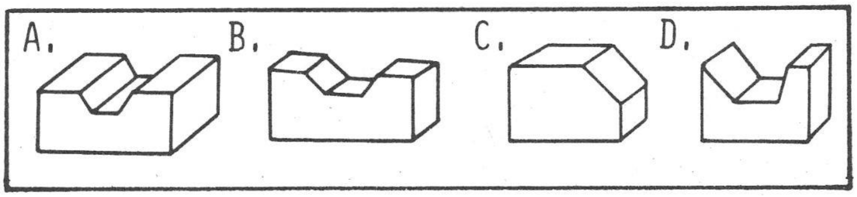
○ A ○ B ○ C ○ D



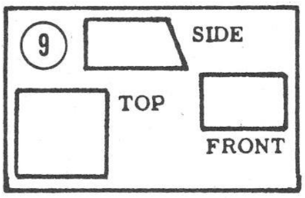


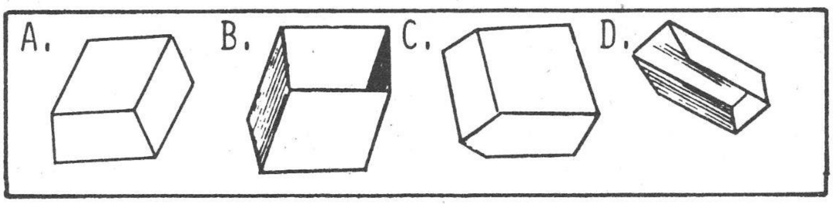
○ A ○ B ○ C ○ D





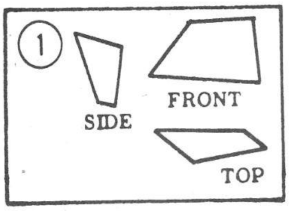
○ A ○ B ○ C ○ D

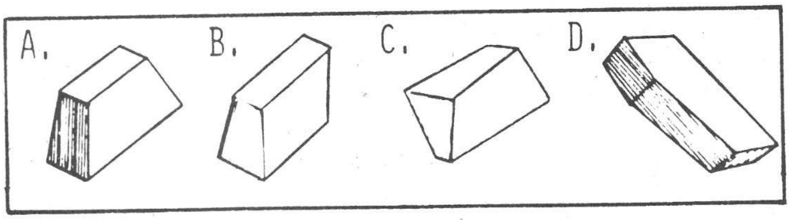




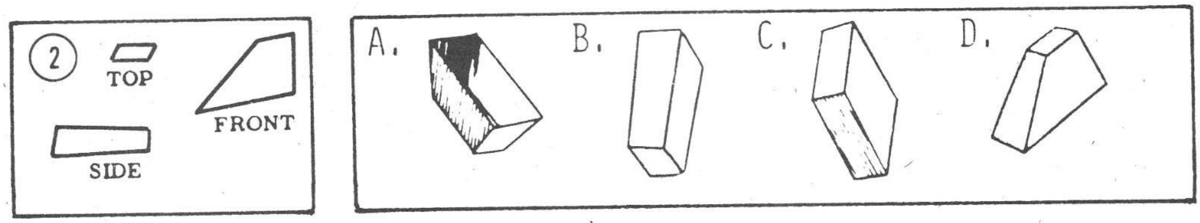
○ A ○ B ○ C ○ D

Test 3

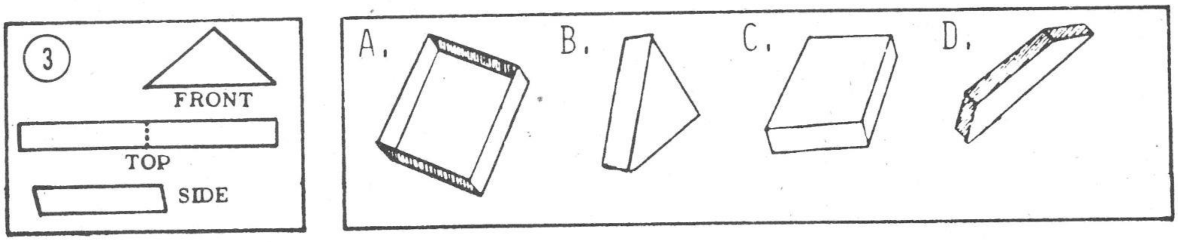




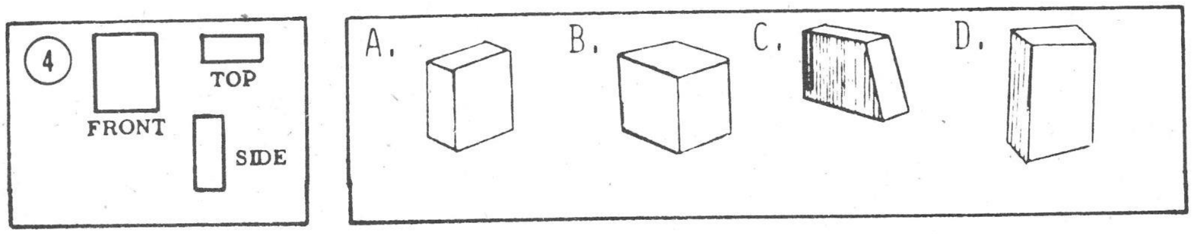
○ A ○ B ○ C ○ D



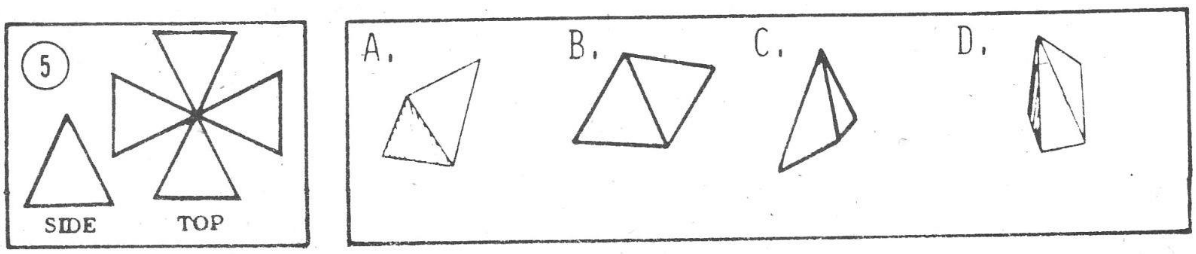
A B C D



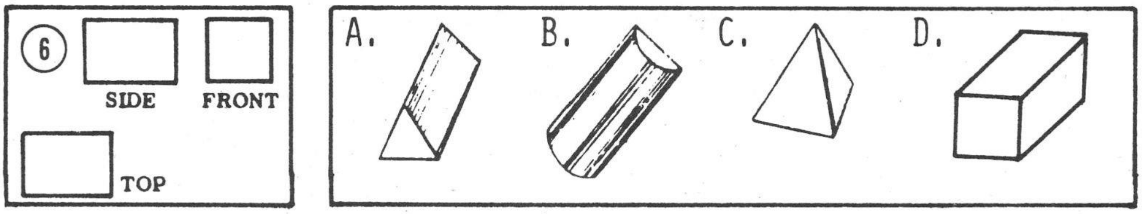
A B C D



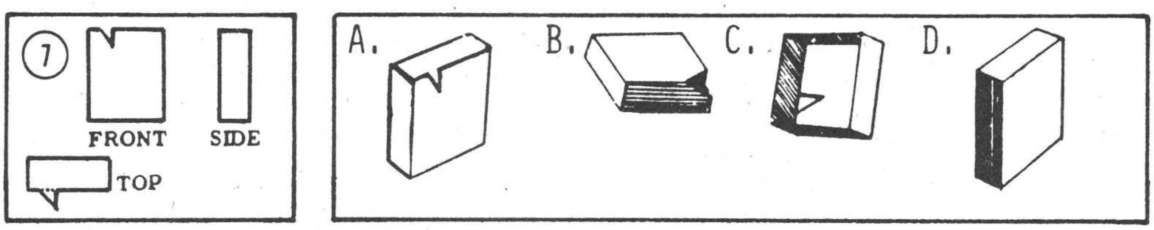
A B C D



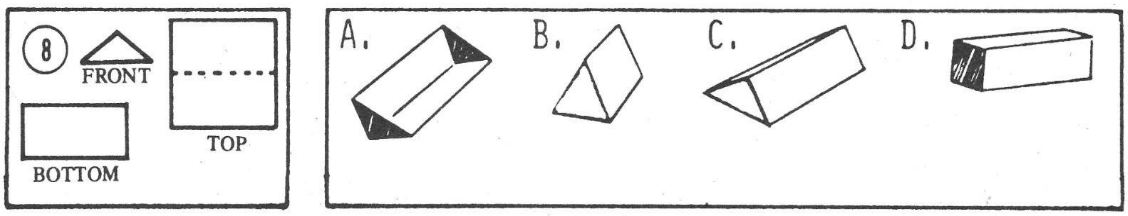
A B C D



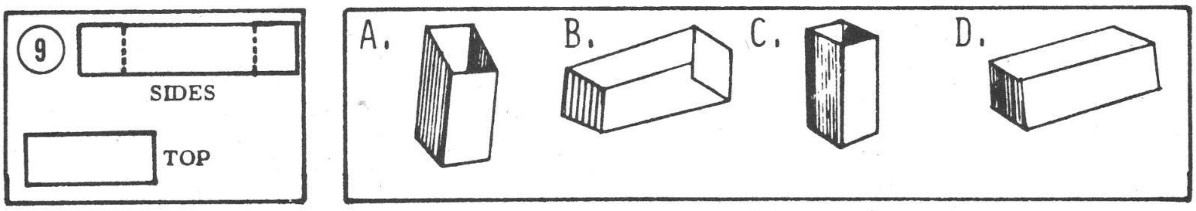
○ A ○ B ○ C ○ D



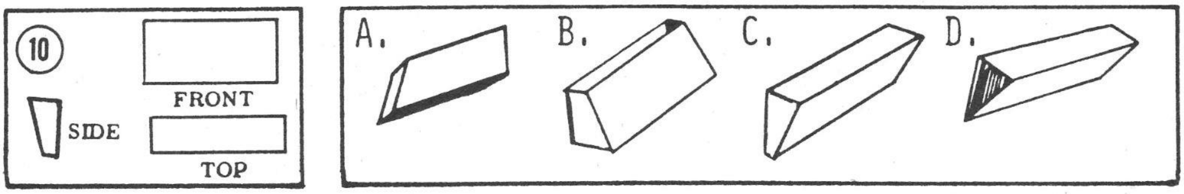
○ A ○ B ○ C ○ D



○ A ○ B ○ C ○ D



○ A ○ B ○ C ○ D



○ A ○ B ○ C ○ D

Thank you! That was the last question. Please hand this sheet back to the researcher.

7.12 Appendix L: Cell knowledge test for Pilot 2

Your Understanding of Cell Biology **Name:**

Try to use your knowledge of cell biology and any other aspects of biology to include as much detail as possible in the space below about your understanding of the following.

Discuss how organelles in a cell will work together to produce and position a sodium-potassium pump (protein) in the plasma membrane

7.13 Appendix M: Worksheet for Pilot 2

Interacting with a Virtual Animal Cell

In this lab activity you will be working with a partner and interacting through a "microscope" (the Oculus Rift headset) with a virtual animal cell using a haptic interface shown below.

You can hold the haptic interface like a pen to touch, manipulate, and investigate the virtual cell. As you move the device, you control the movement of a grey sphere (cursor) in the virtual world through which you can touch and feel the objects.

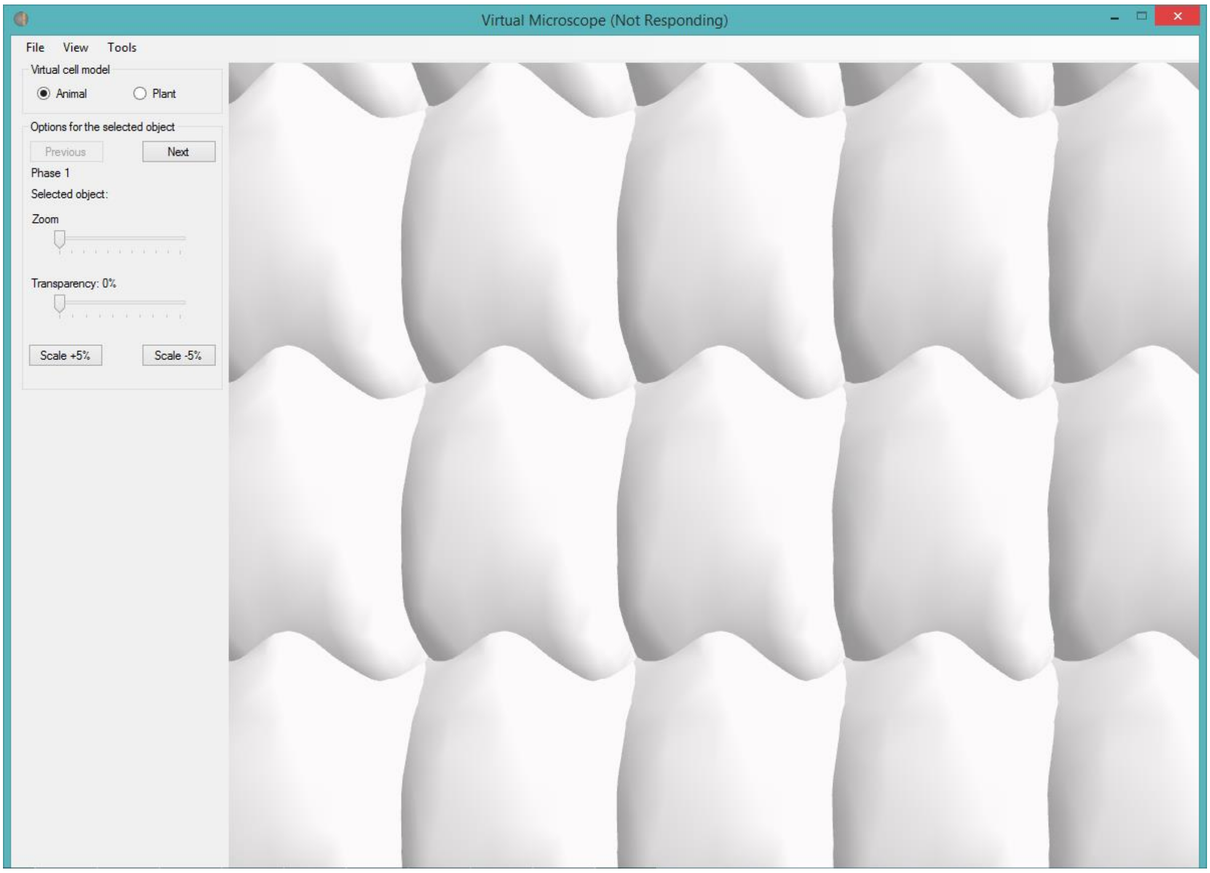
In pairs, you will take turns being the pilot and the navigator. The pilot will control the robot, whereas the navigator will be in control of the worksheet instructions and help the pilot to achieve the task goals by explaining, watching and using the keyboard/mouse when necessary.

Please swap roles after 10 minutes.

Task 1: Multiple Cells

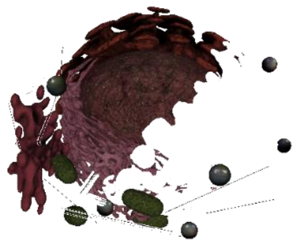
The task starts with the display of a sheet of animal cells on the screen. At this stage, take a look at the cells, you can rotate the view by using the mouse and zoom in/out using the slider on the left pane.

By clicking the Next button on the left pane, you can continue to the next step.



Task 2: Single Cell – identifying the organelles

Single virtual animal cell model is now displayed on the screen.



First you have to remove the cell membrane to see the interior of the cell. You can grab the cell membrane and take it away.

In order to grab an object, first touch the object you want to grab and, while you are in contact press BUTTON1 on the robot, while pressing the button, move the robot and observe that the virtual object is following your motion.

After the cell membrane is removed, investigate the inside of the cell. Try examining an object more closely by either using the robot to bring it closer to your eye or asking your navigator to zoom into the organelle.

Identify the organelles and discuss their function in the cell with your partner.

Task 3: Organelles used in Protein Synthesis and transportation

Discuss how proteins are made and transported in the cell

Place the organelles responsible for the synthesis and transport of a membrane protein, in the order in which they work to create and position a plasma membrane protein into the plasma membrane. Use the boxes along the top of the screen as an aid to ordering the organelles. Discuss with your partner in which order the organelles should be placed and why.

Once you have agreed on the correct order tell the supervisor who will take a picture of your answer.

Now swap places with your partner who will rebuild the cell.

Task 4: Rebuilding the cell

Now use the haptic interface to put the dissected animal cell back together. Discuss with your partner how to place the organelles in the correct places so that once whole, the cell would be able to function normally.

Rotate the cell and make sure that organelles are placed back correctly from every angle.

7.14 Appendix N: Ethics approval for Pilot 2

Research Ethics Office

King's College London

Rm 5.11 FWB (Waterloo Bridge Wing)

London

SE1 9NH

20 May 2016

TO: Megan Tracey

SUBJECT: Confirmation of Registration

Dear Megan,

Thank you for submitting your Research Ethics Minimal Risk Registration Form. This letter acknowledges the receipt of your registration; your Research Ethics Number is **MR/15/16-535**. You may begin collecting data immediately.

Be sure to keep a record your registration number and include it in any materials associated with this research. Registration is valid for **one year** from today’s date. Please note it is the responsibility of the researcher to ensure that any other permissions or approvals (i.e. R&D, gatekeepers, etc.) relevant to their research are in place, prior to conducting the research.

Record Keeping:

In addition, you are expected to keep records of your process of informed consent and the dates and relevant details of research covered by this application. For example, depending on the type of research that you are doing, you might keep:

- A record of the relevant details for public talks that you attend, the websites that visit, the interviews that you conduct

- The 'script' that you use to inform possible participants about what your research involves. This may include written information sheets, or the generic information you include in the emails you write to possible participants, or what you say to people when you approach them on the street for a survey, or the introductory material stated at the top of your on-line survey.
- Where appropriate, records of consent, e.g. copies of signed consent forms or emails where participants agree to be interviewed.

Audit:

You may be selected for an audit, to see how researchers are implementing this process. If audited, you will be expected to explain how your research abides by the general principles of ethical research. In particular, you will be expected to provide a general summary of your review of the possible risks involved in your research, as well as to provide basic research records (as above in Record Keeping) and to describe the process by which participants agreed to participate in your research.

Remember that if you have any questions about the ethical conduct of your research at any point, you should contact your supervisor, the Research Ethics office, or a member of your Department's Research Ethics Panel for advice.

Feedback:

If you wish to provide any feedback on the process you may do so by emailing crec-minrisk@kcl.ac.uk .

We wish you every success with this work.

With best wishes

Research Ethics Office

7.15 Appendix O: Worksheet for Pilot 4

Interacting with a cell membrane model

You will be interacting with a virtual model using a haptic device.
You will work in pairs and discuss your answers. You will take turns being the 'pilot' and the 'co-pilot'.
The pilot will wear the headset that allows you to see the 3D cell membrane model and control the haptic device that allows you to feel and manipulate the model.
The co-pilot will read and explain the worksheet instructions, help the pilot achieve the task goals by discussing the questions and answers and write the answers on the sheet.
After Task 1 the pilot and co-pilot will switch roles for Task 2.

Task 1: Investigating the cell membrane – membrane permeability

Cells are surrounded by a membrane that controls what can enter and exit.

Explore the cell membrane model noting how it feels and looks

1. Try to describe what the model feels like

Protein channels float in the membrane, like icebergs. Can you move one around?

2. Try to describe how it feels

You can see coloured particles moving around. Do they all behave the same?

3. Try to describe what you can see

----

4. Identify the oxygen and glucose particles – what colour and size are they in the model?

Oxygen:		
Glucose:		

5. Which of these particles can cross through the membrane easily? Why do you think it crosses easily?

----

6. Which of the particles cannot cross through the membrane easily? Why?

Task 2: Movement across the cell membrane – Membrane channels

Swap over with your partner now so that you each get a turn at being pilot and co-pilot. Ask the instructor to set up the next task for you.

You are going to investigate in more detail how the membrane controls what enters and leaves the cell.

You can now see a part of the membrane that has a different type of channel from the ones you saw before. Explore the membrane model noting how it feels and looks

7. Try to describe what the membrane feels like and how this channel looks and feels different from previous ones

----

This cell is respiring aerobically. Cells need oxygen and glucose which they use to make ATP. The process produces carbon dioxide and water as waste products.

Try to grab hold of an oxygen molecule and moving it into the cell.

8. Try to describe what you feel and see for oxygen?

Now try moving the glucose into the cell. Is there another way inside?

9. Try to describe what you feel and see for glucose?

----

10. Can you think of an explanation for why glucose can't enter and exit as easily as oxygen?

7.16 Appendix P: Cell knowledge test for Pilot 4

Your understanding of the cell membrane

Cells are surrounded by a membrane called the cell membrane or plasma membrane. This quiz is designed to check what you know about what the cell membrane is like and how it works. Do not worry if you are unsure of the answers. You will be able to learn about cell membranes later.

1) in the spaces below try to write 5 important facts about the cell membrane and try to use as many as you can of the following words: active transport, diffusion, permeable, oxygen, carbon dioxide, glucose, sodium ions, potassium ions, membrane proteins, channel, respiration.

	Fact about the cell membrane	How sure are you about being correct?		
1		Very confident	Quite confident	No idea Guessing
2		Very confident	Quite confident	No idea Guessing
3		Very confident	Quite confident	No idea Guessing
4		Very confident	Quite confident	No idea Guessing
5		Very confident	Quite confident	No idea Guessing

2) Explain why the cell membrane is important for cells in our body

For each of the following statements circle whether you think that the statement is true, false or if you are unsure.

Statement	**True**	**False**	**Unsure**
The plasma membrane is a barrier that stops everything from entering/exiting the cell	True	False	Unsure
The plasma membrane is solid	True	False	Unsure
The plasma membrane is transparent	True	False	Unsure
The plasma membrane contains membrane proteins that sit in a fixed position in the membrane	True	False	Unsure
All membrane proteins are the same, forming channels that allow anything to cross the membrane and enter the cell	True	False	Unsure
Oxygen can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Glucose can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Carbon dioxide can freely enter and exit a cell (does not need a channel)	True	False	Unsure

Sodium can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Glucose is smaller than oxygen	True	False	Unsure
The plasma membrane contains about 20 glucose channels	True	False	Unsure
If there is an equal amount of oxygen inside and outside the cell it will be harder for more oxygen to enter than if there is more oxygen outside	True	False	Unsure
The amount of glucose inside a cell makes no difference to how easy it is for glucose to enter	True	False	Unsure
During aerobic respiration a cell uses oxygen and glucose	True	False	Unsure
During aerobic respiration a cell produces oxygen and water	True	False	Unsure

7.17 Appendix Q: Researcher protocol

Protocol for researchers Haptics VR data collection 2806 17

Introduction

Ideally, we want the students to be able to work on this by following the sheet and working collaboratively in their pair without our support because we need to see how well the task works and what the issues are. Also, we want to know what they learn by interacting with the model and each other rather than interacting with us. In the real classroom situation, there would be a teacher, but the teacher would be managing/interacting with about 14 other pairs as well. So, we need to be, as researchers, – observing and only intervening when really necessary.

1) At the start reassure them by saying there are no right answers and we are hoping they will help us to improve the system. (I noticed that while most of them were confident yesterday, but some were a bit anxious at the start and I heard one boy asking his friend "are you scared?".) Ask them to read the sheet and check whether they understand the task. Answer any questions about the tasks at that point.

2) Intervene when/if:

    a. the software is not working properly:

    b. they are having trouble with the equipment

    c. they seem to be stuck – but avoid giving them answers

3) don't chivvy them along too much – inevitably they will spend some time exploring which may seem unproductive but maybe useful for us to know.

4) Don't answer their questions about factual issues and content of the topic but instead tell them to just write what they think and that we want to know their ideas. The problem is once you start answering questions typically, they will ask more and more.

5) Try not to speak to loudly because we are audio recording in 2 places in the room and our voices carry

7.18 Appendix R: SRT for Pilot 4 (including Solid Figure Turning)

Spatial Relations

Name: ___________________

Spatial Views

Directions:

Each question in the following tests consists of a numbered picture showing top, front and side representations of a three-dimensional object.

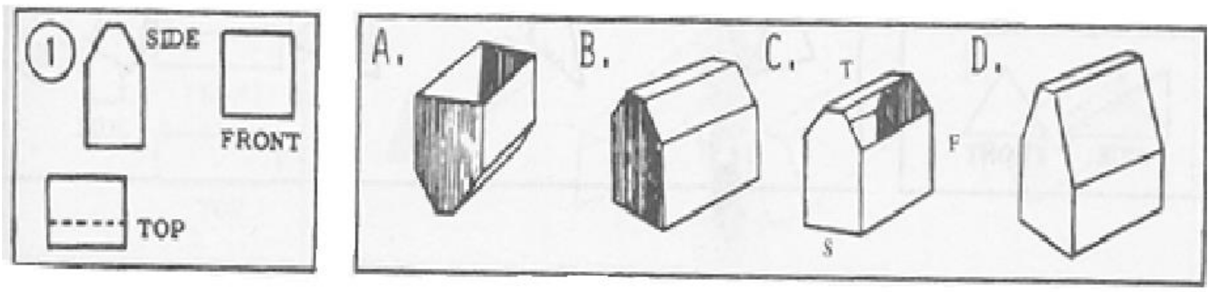
DASHED LINES indicate FOLDS.

To the right of the numbered representations are four pictures, lettered A,B,C and D.

You are to SELECT ONE OF THE PICTURES that would have the TOP, FRONT and SIDE representations shown in the numbered picture.

Please TICK the circle of your answer (A, B, C or D) beneath the question.

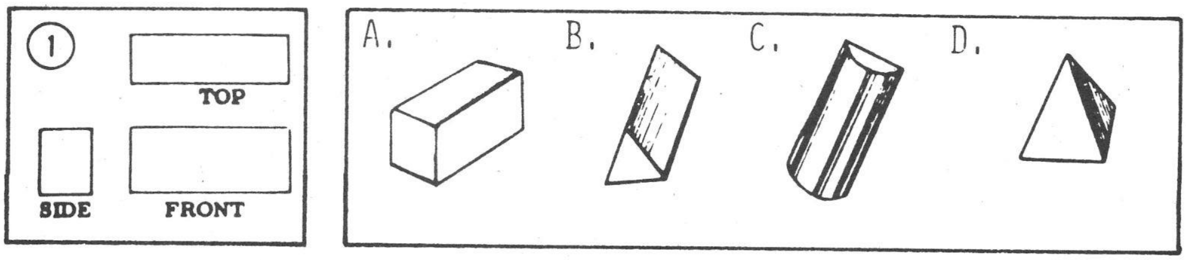
Example Question



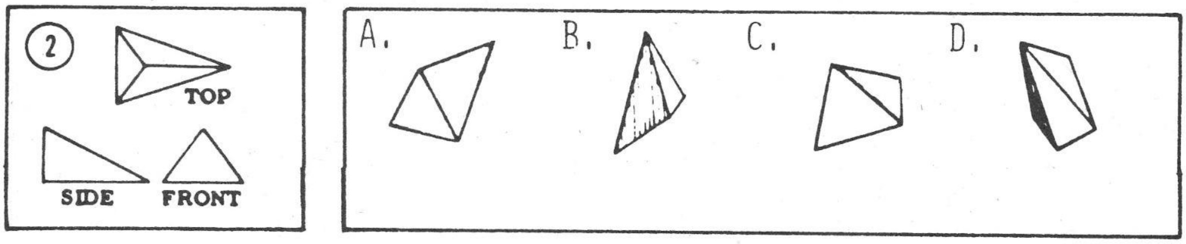
A B C D

The first frame of this question shows the top, side, and front representations of one of the objects labelled A, B, C and D. At first glance, you can eliminate D since the side view is taller and thinner than the side representation shown in the first frame. Alternatives A and B can be eliminated because the offer front representations which are too long and narrow for the given front view. Alternative C is the only one of the four figures that could have the top, side and from representations shown in the numbered picture.

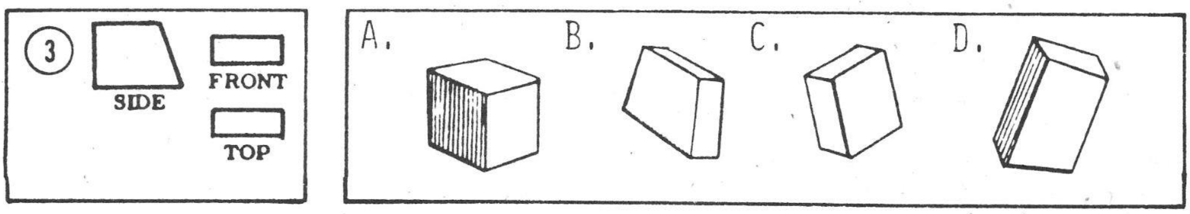
Test 1



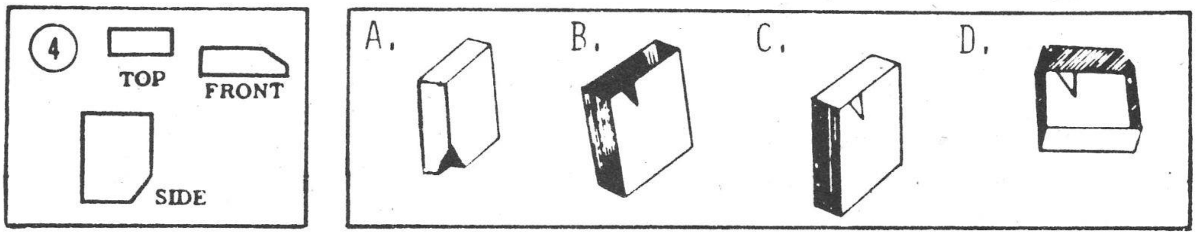
A B C D



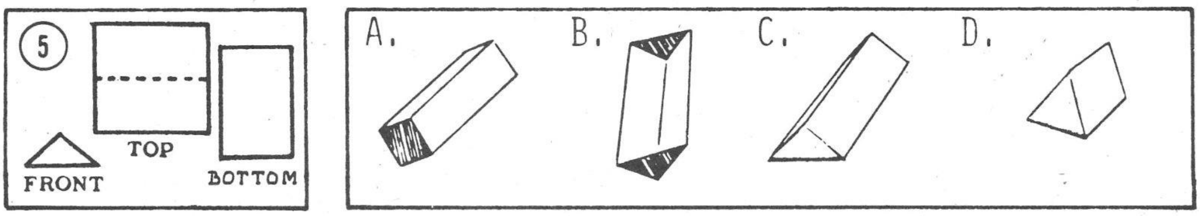
A B C D



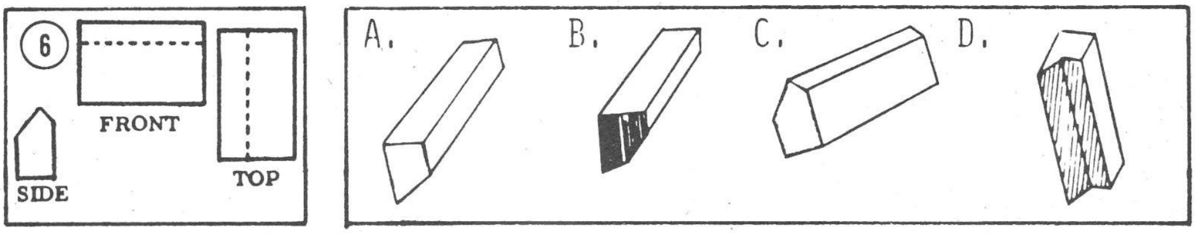
A B C D



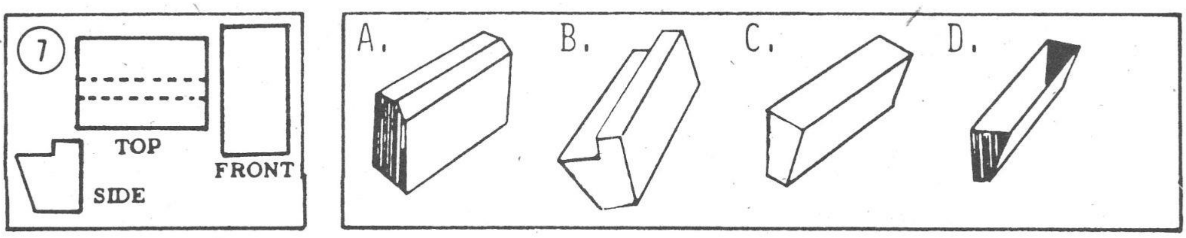
A B C D



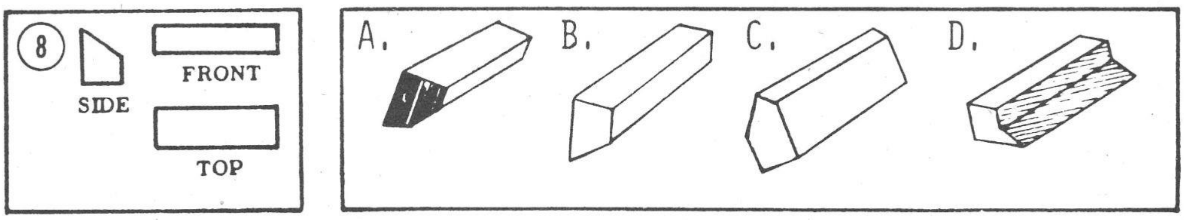
A B C D



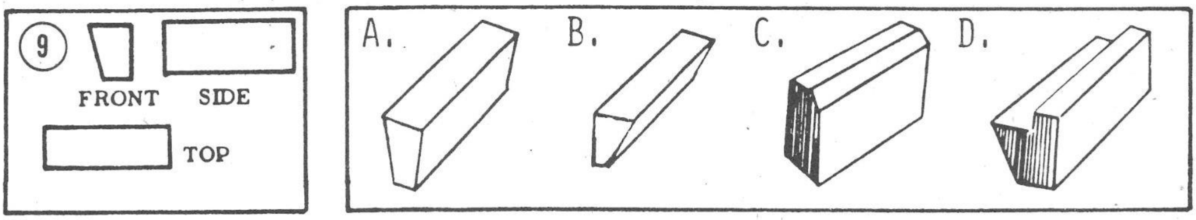
A B C D



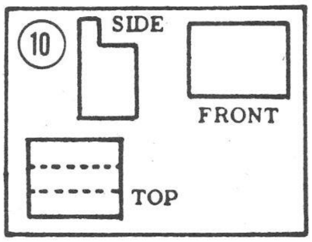
A B C D

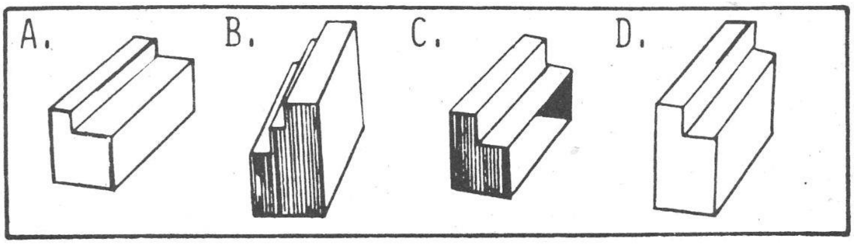


A B C D



A B C D





A B C D

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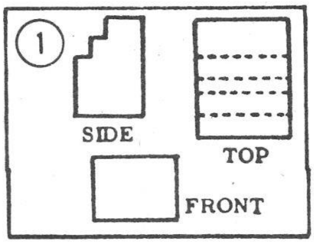
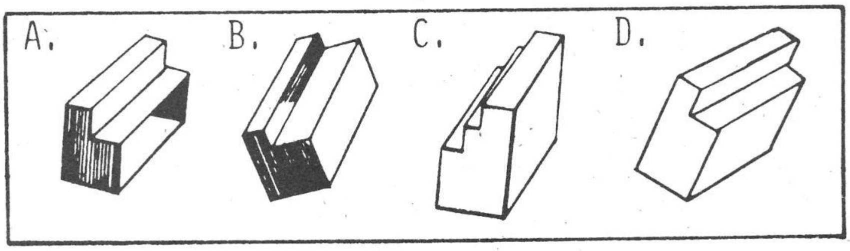
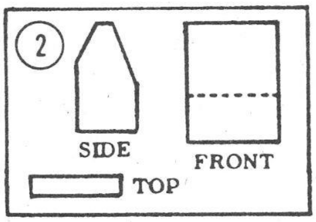
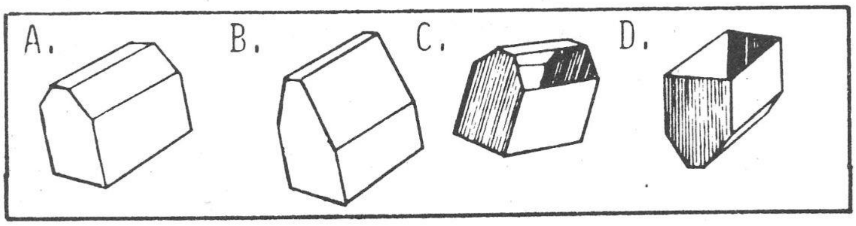


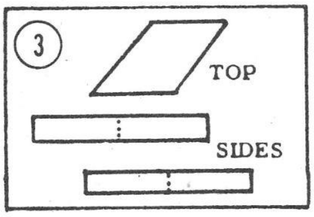


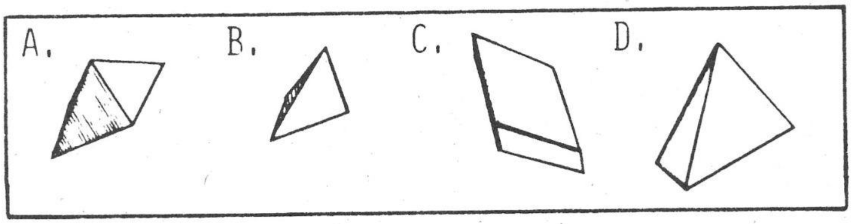
A B C D



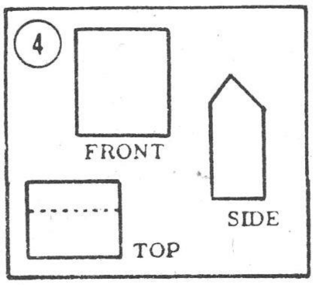


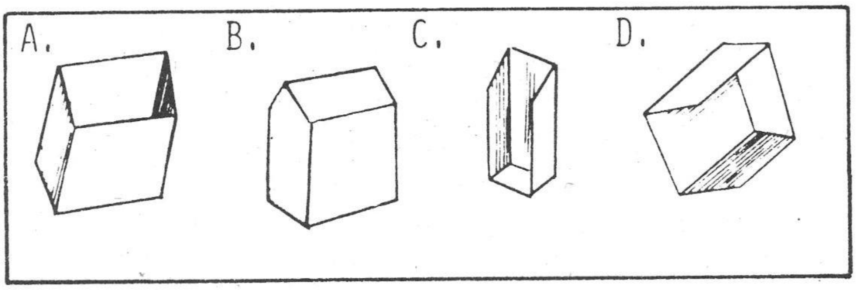
A B C D





○ A ○ B ○ C ○ D





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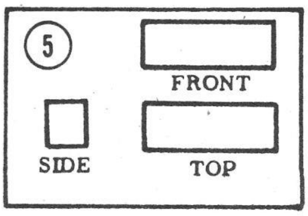

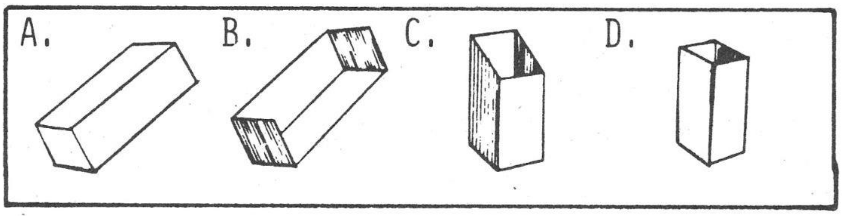

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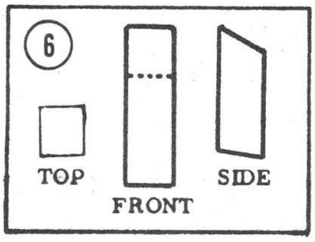
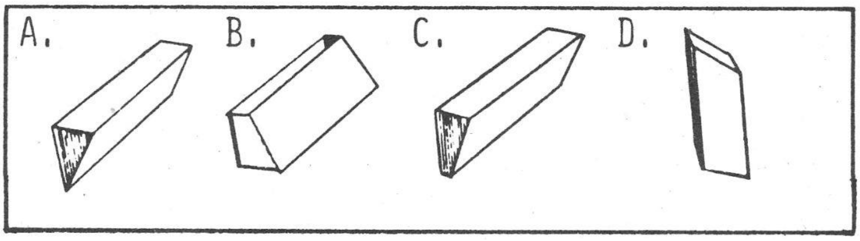
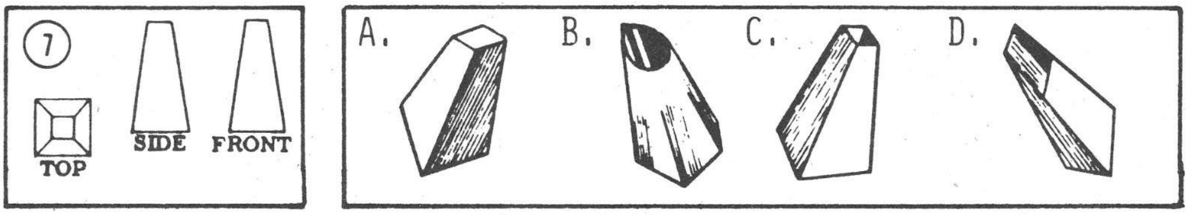




○ A ○ B ○ C ○ D



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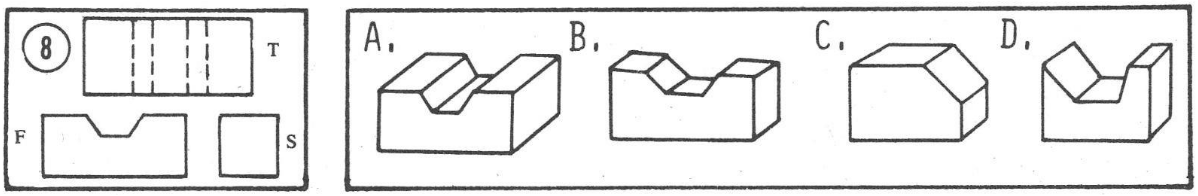

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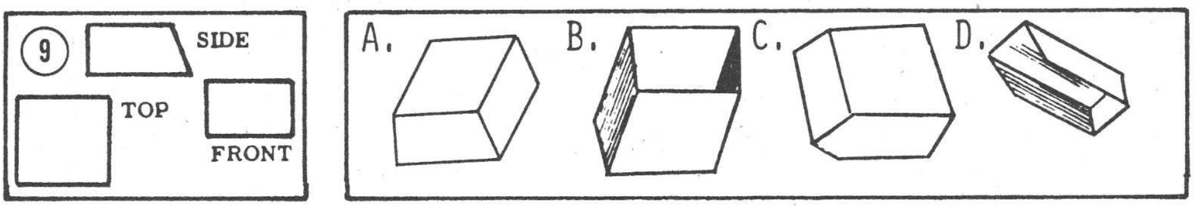
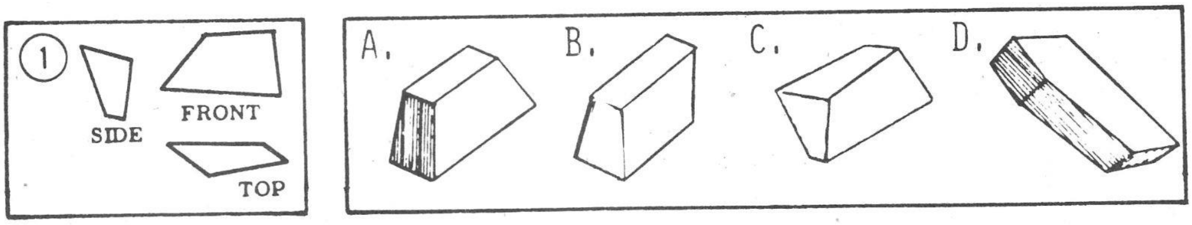


○ A ○ B ○ C ○ D

Test 3



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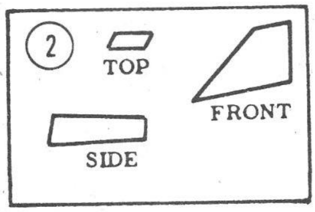
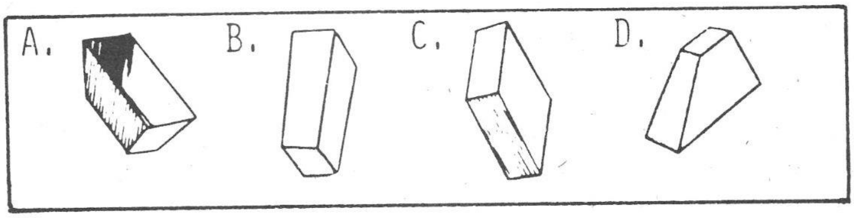
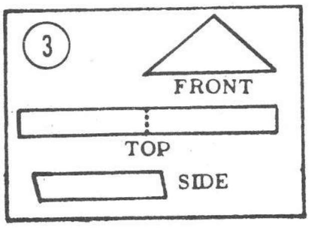
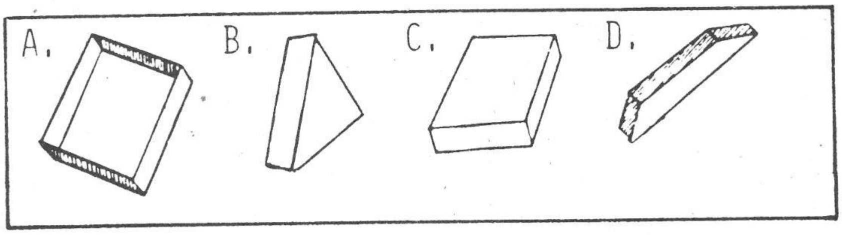




○ A ○ B ○ C ○ D





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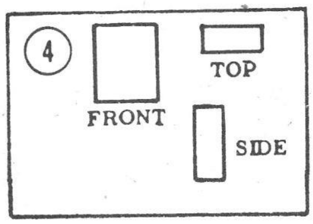
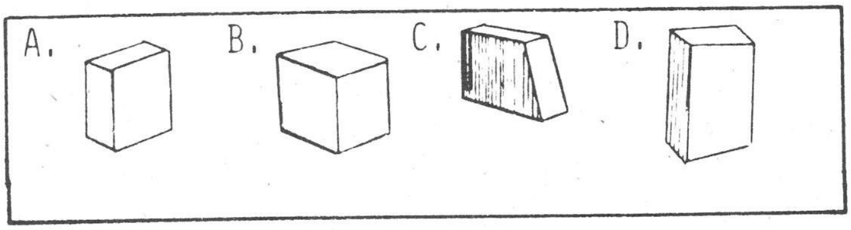
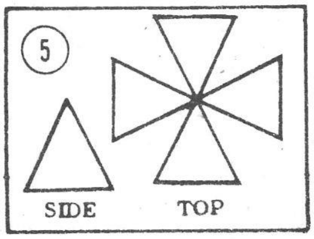
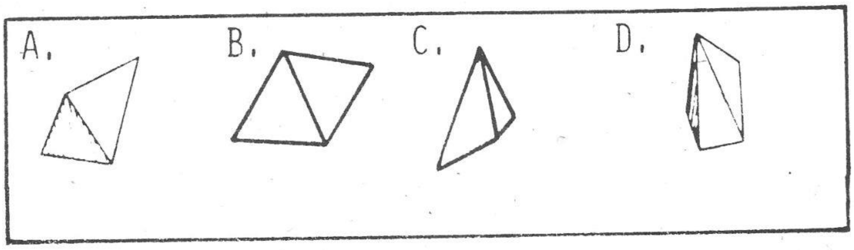




○ A ○ B ○ C ○ D





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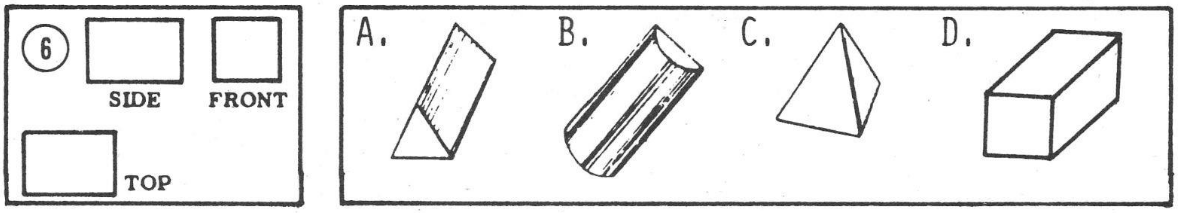
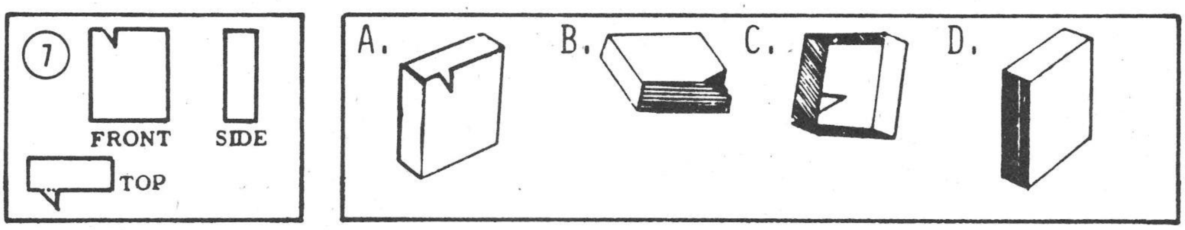
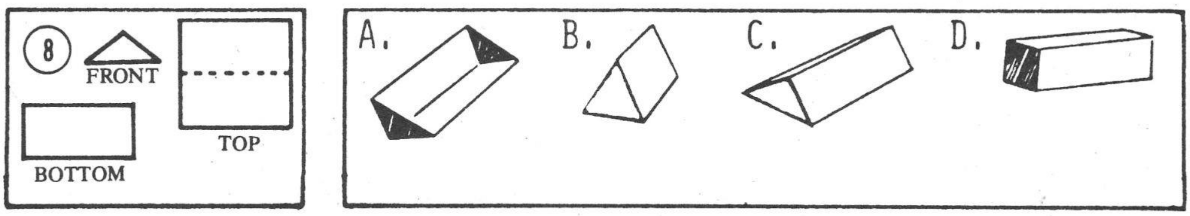


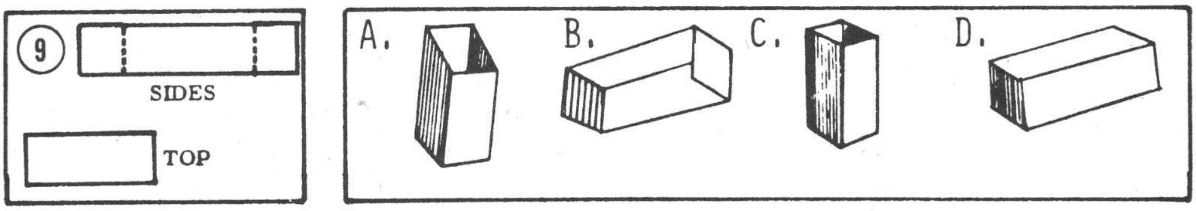
A B C D



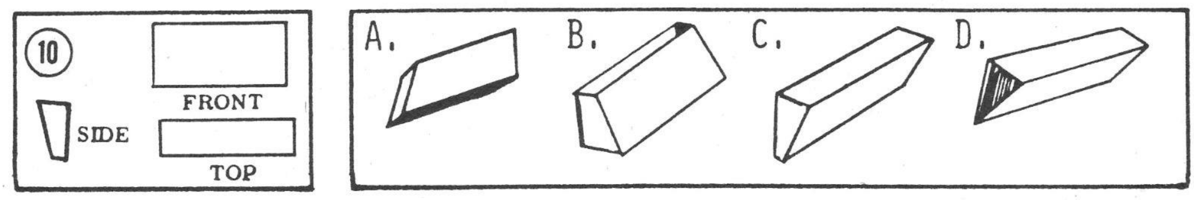
A B C D



A B C D



A B C D



○ A ○ B ○ C ○ D

Solid Figure Turning

Directions:

Each numbered figure is made up of cubes or other forms which are assumed to be glued together.

Next to each numbered figure are four lettered figures.

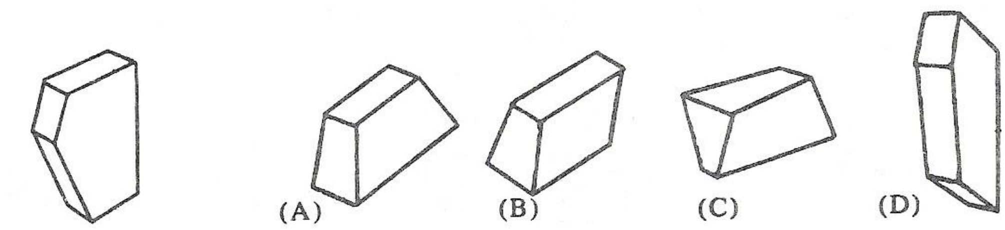
Choose the one lettered figure (A, B, C or D) which is the numbered figure turned to a different position.

In order to select the correct answer, you may have to mentally turn figures over, turn them around or turn them both over and around.

Please TICK the circle of your answer (A, B, C or D) beneath the question.

Example Question:

(1)

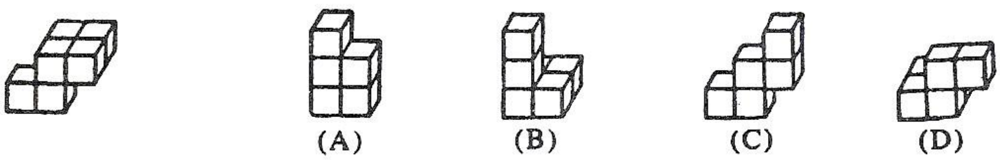


A B C D

This example question illustrates a Solid Figure Turning question. Which of the alternatives lettered A, B, C and D represents figure 1 in a different position? Figure 1 consists of a solid figure with 7 faces. Alternative D, which tilts the figure backwards to expose the bottom surface, is the only alternative which could properly represent the figure in a different position.

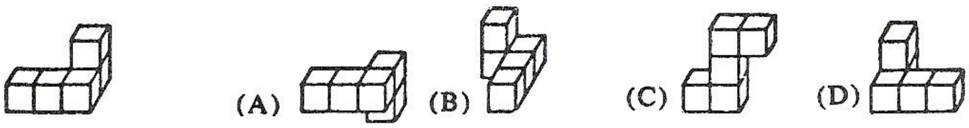
Test 1

(1)



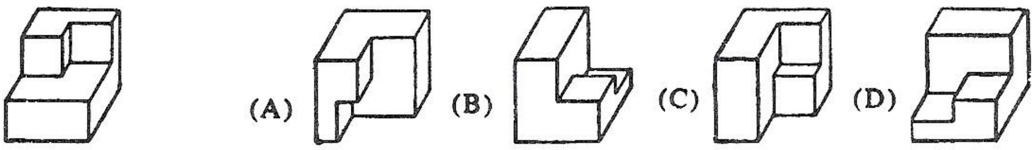
A B C D

②



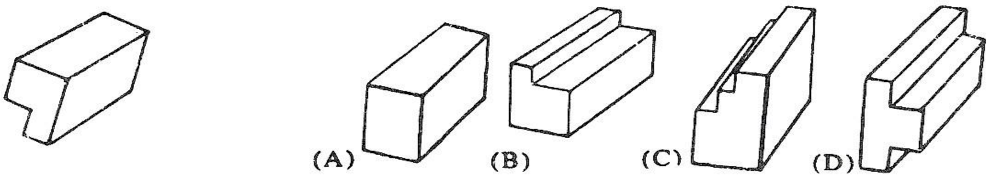
○ A ○ B ○ C ○ D

③



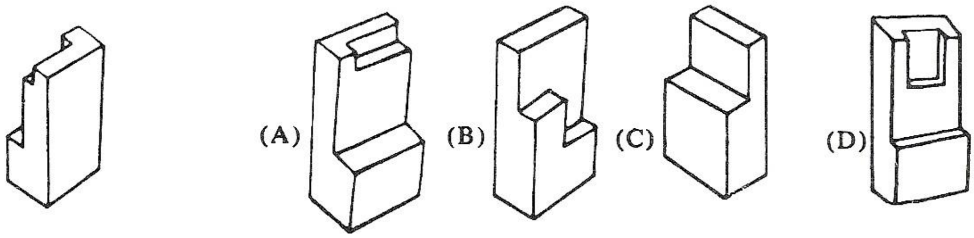
○ A ○ B ○ C ○ D

④



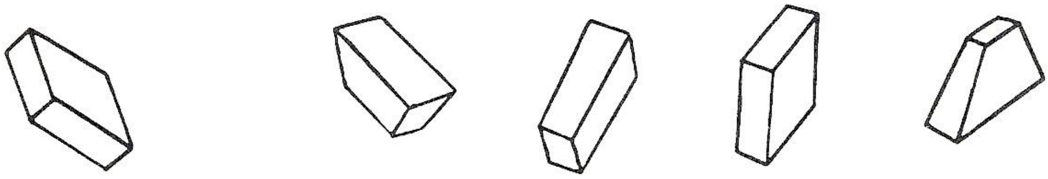
○ A ○ B ○ C ○ D

⑤



○ A ○ B ○ C ○ D

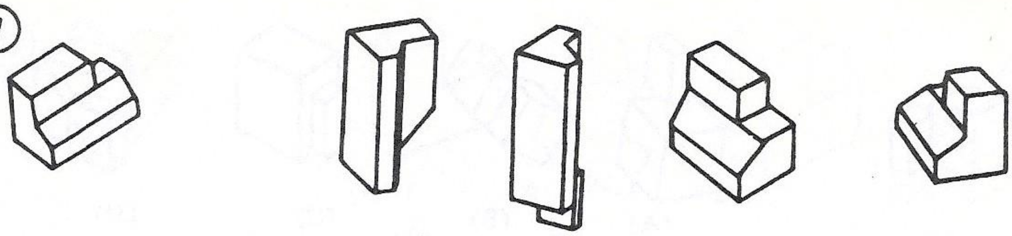
6



(A) (B) (C) (D)

○ A ○ B ○ C ○ D

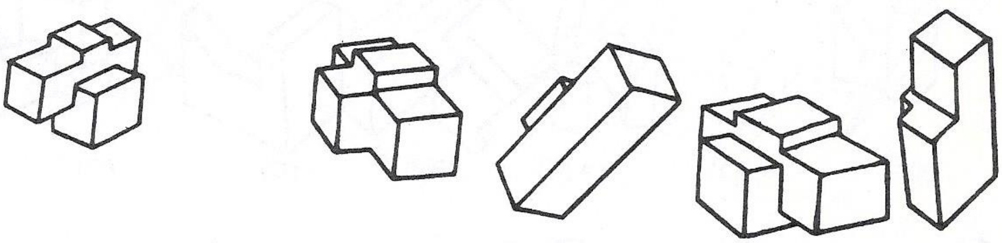
7



(A) (B) (C) (D)

○ A ○ B ○ C ○ D

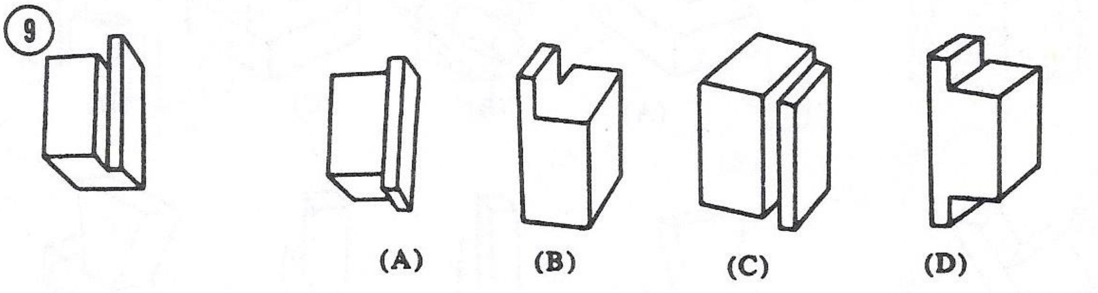
8



(A) (B) (C) (D)

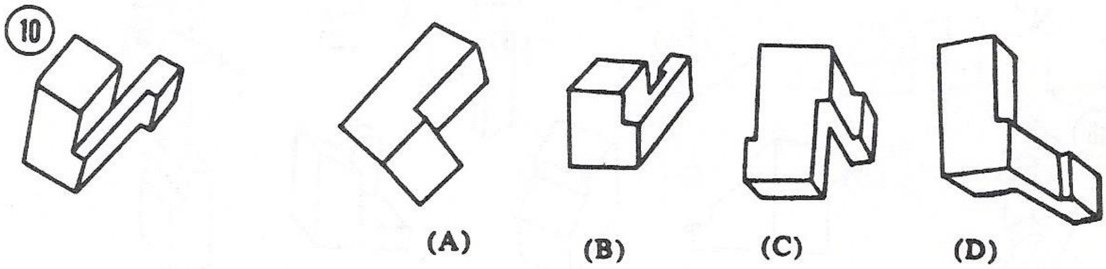
○ A ○ B ○ C ○ D

9



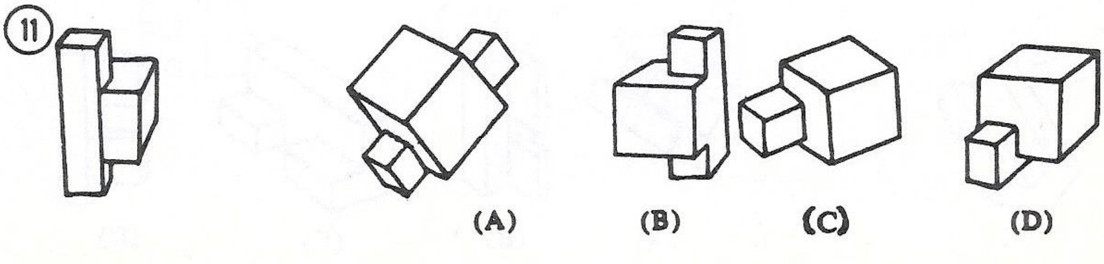
A B C D

10



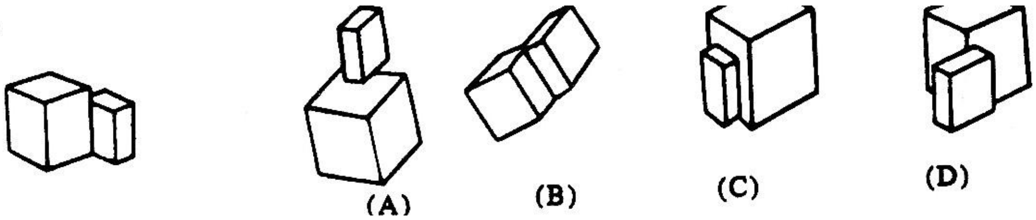
A B C D

11



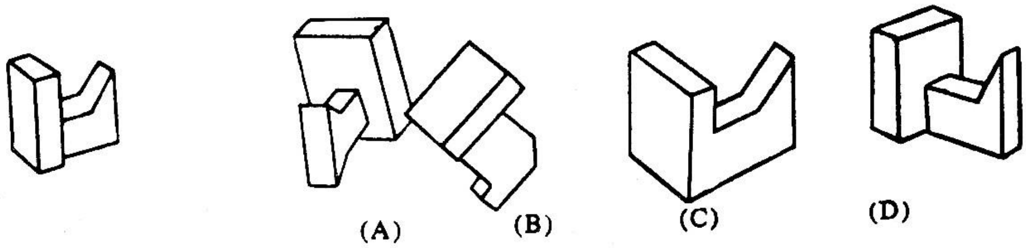
A B C D

12



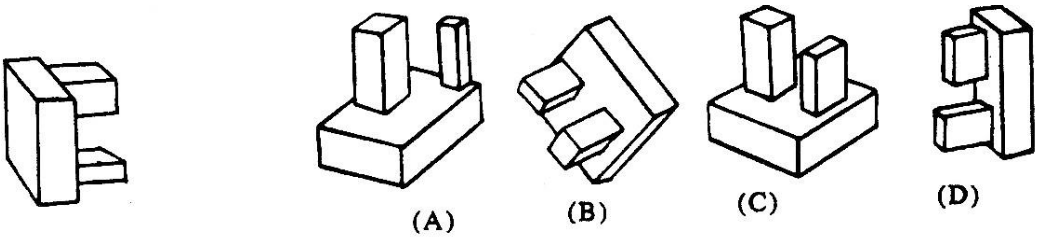
○ A ○ B ○ C ○ D

13



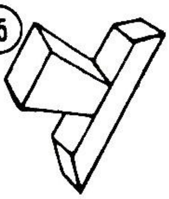
○ A ○ B ○ C ○ D

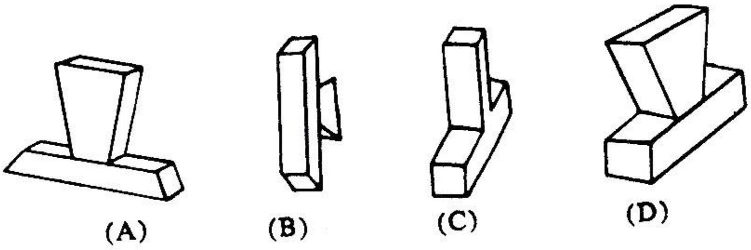
14



○ A ○ B ○ C ○ D

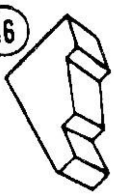
15

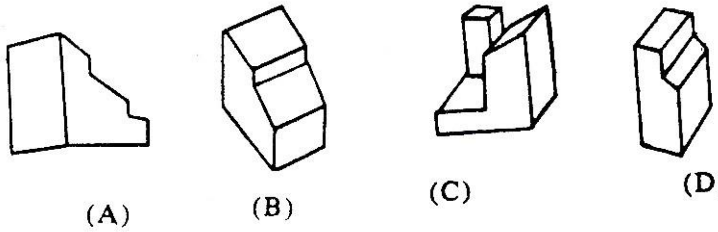




○ A ○ B ○ C ○ D

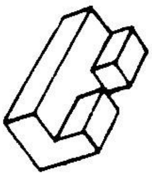
16

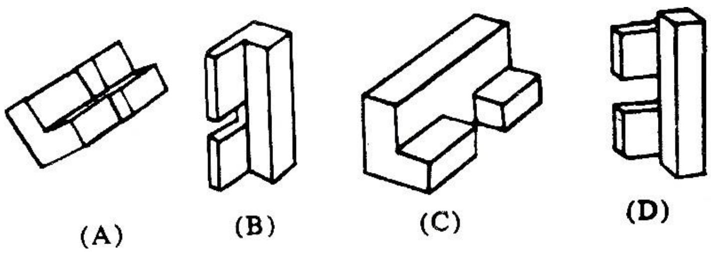




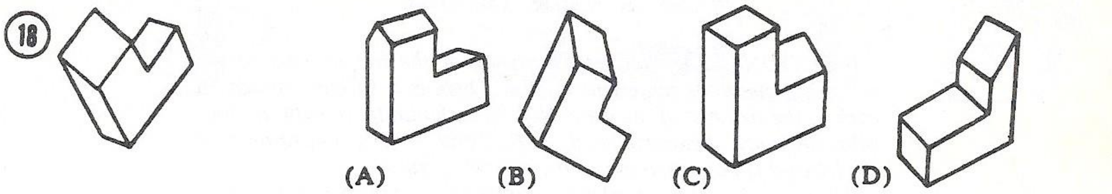
○ A ○ B ○ C ○ D

17

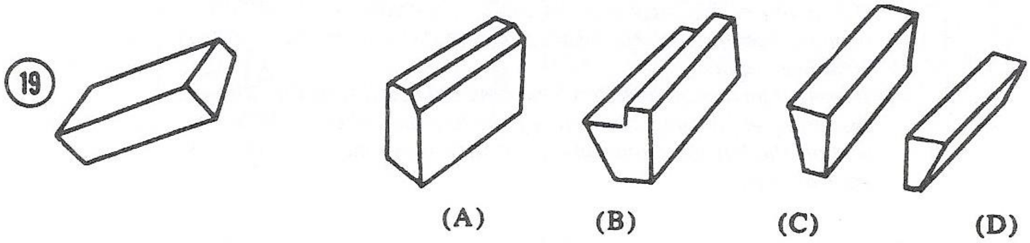




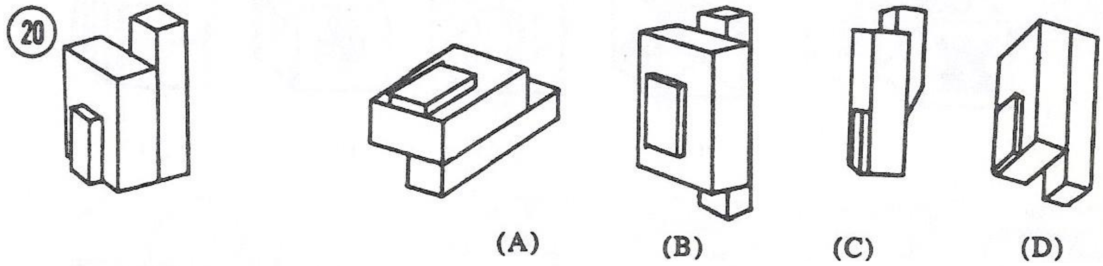
○ A ○ B ○ C ○ D



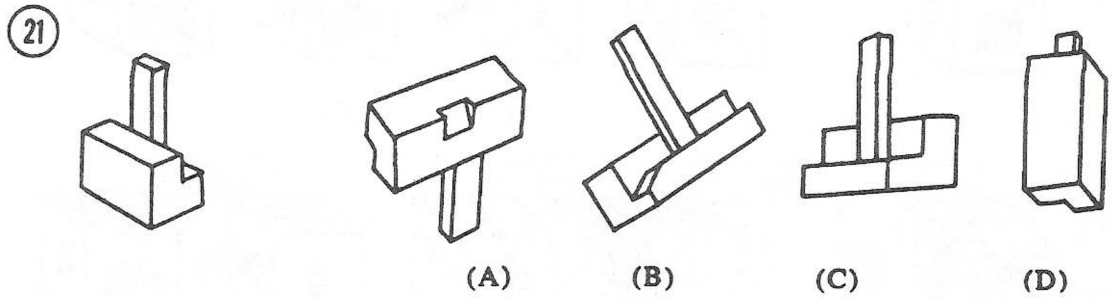
A B C D



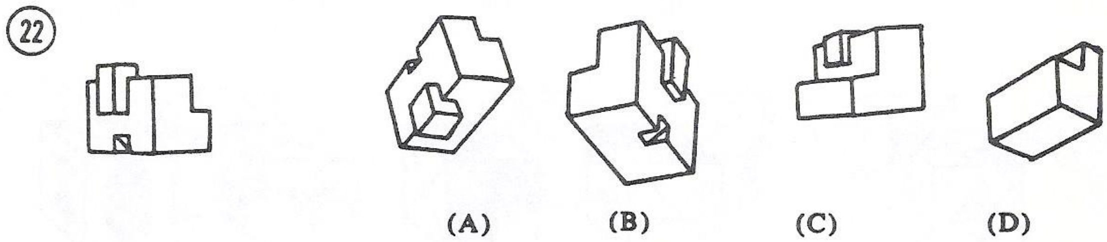
A B C D



A B C D



○ A ○ B ○ C ○ D



○ A ○ B ○ C ○ D

Thank you! That was the last question. Please hand this sheet back to the researcher.

7.19 Appendix S: Ethical approval for Pilot 4

Megan Tracey

Research Ethics Office

Franklin Wilkins Building
5.9 Waterloo Bridge Wing
Waterloo Road
London SE1 9NH
Telephone 020 7848 4020/4070/4077
rec@kcl.ac.uk

KING'S College LONDON

Megan Tracey

23 June 2017

Dear Megan

LRS-16/17-3067

Thank you for submitting your application for the above project. I am pleased to inform you that your application has now be approved with the provisos indicated at the end of this letter. All changes must be made before data collection commences. The Committee does not need to see evidence of these changes, however supervisors are responsible for ensuring that students implement any requested changes before data collection commences.

Ethical approval has been granted for a period of **three years** from23 June 2017 You will not be sent a reminder when your approval has lapsed and if you require an extension you should complete a modification request, details of which can be found here: http://www.kcl.ac.uk/innovation/research/support/ethics/applications/modifications.aspx

Please ensure that you follow the guidelines for good research practice as laid out in UKRIO's Code of Practice for research: http://www.kcl.ac.uk/innovation/research/support/conduct/cop/index.aspx

Any unforeseen ethical problems arising during the course of the project should be reported to the panel Chair, via the Research Ethics Office.

Please note that we may, for the purposes of audit, contact you to ascertain the status of your research.

We wish you every success with your research.

Yours sincerely,
Miss Annah Whyton

Senior Research Ethics Officer

For and on behalf of:
E&M Research Ethics Panel

Major issues (will require substantial consideration by the applicant before approval can be granted)

Minor issues related to application (the reviewer should identify the relevant section number before each comment)

Please consider how students will be approached to take part in the study such that the pressure to participate is minimised. For example, instead of the teachers approaching the students, consider approaches that might be more neutral (e.g. school administrator / introducing the study yourself).

You should also highlight to the students that participation in the study will not have any bearing on their grades.

Minor issues related to recruitment documents

Information sheet for students:

- Consider using more simple language to describe the nature of the study.

Page 1 of 2

7.20 Appendix T: Information sheets for Pilot 4

INFORMATION SHEET FOR PARTICIPANTS

REC Reference Number: LRS-16/17-3067

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title

Using Haptics to Increase Understanding in Cell Biology

Invitation Paragraph

We would like to invite you to take part in this research. You should only take part if you want to; choosing not to take part will not disadvantage you in anyway and will have no effect on your grades or schoolwork. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

Overall, we would like to develop a 3D learning environment with visual and touch (haptic) feedback that encourages co-operation and allows students to hypothesise and explore scientific concepts.

This study is a pilot to introduce a prototype haptic learning system providing a virtual 3D cell membrane with touch feedback which students can view and manipulate. The study also aims to pilot some psychometric tests including those looking at spatial skills, fine dexterity and cell membrane knowledge.

Why have I been invited to take part?

We are inviting all Year 8 students to take part in this study.

Do I have to take part?

Participation is voluntary. You do not have to take part. Choosing not to take part in the study will not have any effect on your schoolwork or grades. You should read this information sheet and if you have any questions you should ask the research team.

What will happen to me if I take part?

If you decide to take part, you will be given a consent form to indicate your willingness to participate in the study and agree to the use of your anonymised data. Even if you have decided to take part, you are still free to withdraw at any time without giving a reason.

After expressing your consent, you will take part in the following activities before using the haptic device:

1. A short test of your existing knowledge of cell membranes. You are not expected to know much (if anything) on this subject yet, so don't worry about answering correctly, and it is fine to answer 'unsure' if you need to.
2. A fine dexterity test (4 mins) which will involve placing as many metal parts on small pins using fingers and tweezers as you can in 2 minutes.
3. A spatial block design test where you will use your hands to rearrange blocks that have various colour patterns on different sides to match a pattern shown to you.
4. A paper based spatial test about Spatial Views and figure turning of 3D objects

Following this, you will then take part in the haptic activity, where you will be video recorded. There will be a short tutorial for you to get used to the equipment. Then, in pairs, you will take turns being the 'pilot' and the 'co-pilot'. The pilot will wear the oculus rift viewer showing the cell membrane model and use 3D haptic device to manipulate the cell. The co-pilot will be in control of the worksheet instructions and help the pilot achieve the task goals and identify features by being able to view the membrane model on the computer screen.

Once the activity is complete, you will be asked to fill out the online feedback form giving your views on the activity/system and how you found the experience (5 mins). You will also be given the test of cell knowledge again (10 mins). Finally, the researcher team will ask you some questions about your experience (10 mins).

This will be the end of the pilot. In the event of you wishing to withdraw from the study after submitting your data, you will still be able to do so up to 21/7/17.

What are the possible benefits and risks of taking part?

There are no foreseeable risks in participating in the study. However, the study will give you the opportunity to experience new haptic technology which may help students in their learning.

Will my taking part be kept confidential?

The information you provide will be treated with the strictest confidentiality and will be held securely until the research is finished. The data for analysis will be anonymised and your real name will never be used. It will not possible to identify you individually from any reports and papers that are written. There will be no possibility of you as individuals being linked with the data.

The UK Data Protection Act 1998 will apply to all information gathered within the interviews and held on password-locked computers.

What will happen to the results of the study?

The results of this study will be used to improve the haptic system and assess the appropriateness of the psychometric tests for future research with your school. The results may also be reported through publications in the field of Educational research.

Who should I contact for further information?

If you have any questions or require more information about this study, please contact me using the following contact details:

Researcher name: Megan Tracey
Researcher Email: megan.tracey@kcl.ac.uk

What if I have further questions, or if something goes wrong?

If this study has harmed you in any way or if you wish to make a complaint about the conduct of the study you can contact King's College London using the details below for further advice and information:

Research Supervisor: Dr. Mary Webb
Supervisor email: mary.webb@kcl.ac.uk

Supervisor Address: Dr Mary Webb
School of Education, Communication and Society
Waterloo Bridge Wing
Franklin-Wilkins Building
Waterloo Road
London
SE1 9NH

Thank you for reading this information sheet and for considering taking part in this research.

7.21 Appendix U: Parental and student consent forms for Pilot 4

LETTER OF PARENTAL CONSENT

Dear Parent or Guardian,

(Insert school name here) is currently in partnership with the University of Reading and King's College London in a research project aiming to develop new learning experiences in Science. Researchers are currently recruiting year 8 students to take part, and your child has been invited to participate.

This study will give students the opportunity to use a virtual reality learning system, which will provide a virtual 3D cell membrane with tactile feedback which students can view and manipulate. Students will work in pairs to explore the virtual 3D cell membrane and complete a worksheet encouraging discussion and co-operative learning. With their permission, students' interactions during this activity will be video recorded. In addition, students will also complete some short assessments of spatial ability, fine dexterity and their knowledge of cell biology. The session will close by asking students some questions about their experience, which will also be recorded. The entire session will last approximately 90 minutes.

Ethical approval will be approved by King's College London and the students will remain completely anonymous throughout the study. The school's child protection policy will be adhered to and participation is entirely voluntary, which will be explained to each student before the session. It will be made clear that they will be free to withdraw at any time should they not wish to continue for any reason and any data collected will be destroyed.

If you give your permission for your child to participate in this study, would you kindly complete the permission slip and return this to your child's class teacher as soon as possible. In the meantime, should you have any questions or would like to have access to the materials used in the study, please do not hesitate to contact the research team, whose details are below.

Thanking you in advance,

Megan Tracey,

PhD Student

Email: megan.tracey@kcl.ac.uk

Research Supervisor: Dr. Mary Webb

Supervisor email: mary.webb@kcl.ac.uk

Ethics Protocol No:

Permission Slip

Name of Student:

I do/do not give my permission for my child to participate in the study.

Signature ___________________________

CONSENT FORM FOR PARTICIPANTS IN RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

KING'S College LONDON

Title of Study:

Using Haptics to Increase Understanding in Cell Biology-Materials Pilot

King's College Research Ethics Committee Ref:

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Please tick

I confirm that I understand that by ticking/initialling each box I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes mean that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element I may be deemed ineligible for the study. ☐

Please tick

1. I confirm that I have read and understood the information sheet for the above study. I have had the opportunity to consider the information and asked questions which have been answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. Furthermore, I understand that I will be able to withdraw my data up to 21/7/17. ☐

3. I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998.

4. I understand that my information may be subject to review by responsible individuals from the College for monitoring and audit purposes.

5. I understand that confidentiality and anonymity will be maintained, and it will not be possible to identify me in any publications.

6. I agree that the research team may use my data for future research and understand that any such use of identifiable data would be reviewed and approved by a research ethics committee. (In such cases, as with this project, data would/would not be identifiable in any report).

7. I understand that the information I have submitted will be published as a report and I wish to receive a copy of it.

8. I consent to being audio/video recorded.

9. I consent that my audio/video may be used at public events, such as academic conferences.

Name of Participant	**Date**	**Signature**
Name of Researcher	**Date**	**Signature**

7.22 Appendix V: Cell knowledge tests for Pilot 4

Your understanding of the cell membrane

Cells are surrounded by a membrane called the cell membrane or plasma membrane. This quiz is designed to check what you know about what the cell membrane is like and how it works. Do not worry if you are unsure of the answers. You will be able to learn about cell membranes later.

1) in the spaces below try to write 5 important facts about the cell membrane and try to use as many as you can of the following words: active transport, diffusion, permeable, oxygen, carbon dioxide, glucose, sodium ions, potassium ions, membrane proteins, channel, respiration.

	Fact about the cell membrane	How sure are you about being correct?		
1		Very confident	Quite confident	No idea Guessing
2		Very confident	Quite confident	No idea Guessing
3		Very confident	Quite confident	No idea Guessing
4		Very confident	Quite confident	No idea Guessing
5		Very confident	Quite confident	No idea Guessing

2) Explain why the cell membrane is important for cells in our body

For each of the following statements circle whether you think that the statement is true, false or if you are unsure.

Statement	**True**	**False**	**Unsure**
The plasma membrane is a barrier that stops everything from entering/exiting the cell	True	False	Unsure
The plasma membrane is solid	True	False	Unsure
The plasma membrane is transparent	True	False	Unsure
The plasma membrane contains membrane proteins that sit in a fixed position in the membrane	True	False	Unsure
All membrane proteins are the same, forming channels that allow anything to cross the membrane and enter the cell	True	False	Unsure
Oxygen can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Glucose can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Carbon dioxide can freely enter and exit a cell (does not need a channel)	True	False	Unsure

Sodium can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Glucose is smaller than oxygen	True	False	Unsure
The plasma membrane contains about 20 glucose channels	True	False	Unsure
If there is an equal amount of oxygen inside and outside the cell it will be harder for more oxygen to enter than if there is more oxygen outside	True	False	Unsure
The amount of glucose inside a cell makes no difference to how easy it is for glucose to enter	True	False	Unsure
During aerobic respiration a cell uses oxygen and glucose	True	False	Unsure
During aerobic respiration a cell produces oxygen and water	True	False	Unsure

7.23 Appendix W: Semi-structured interview questions for Pilot 4

Semi-Structured Interview Questions

The System

1. How easy did you find the haptic system to use?

2. Was there anything you particularly liked about the system? Why?

3. What would you change about the system? Why?

4. In this activity, you worked in a pair. How easy was it to work collaboratively whilst using the system?

5. Were there any barriers to working together effectively?

Learning

6. If anything, what have you learned about cells today?

7. What do you think were the advantages for your learning of working together in pairs?

8. Did you like learning collaboratively in pairs in this activity?

9. Do you think being able to "feel" the membrane and particles virtually can help you learn better? Why?

10. Do you think being able to move the particles through the membrane can help you learn better? Why?

7.24 Appendix X: Findings for Pilot 4 including answer changes from pre to post-test depicted with bar graphs

June 2017 Pilot findings

t-test to compare the pre-activity cell knowledge scores and post-activity scores

A paired sample t-test found that there is a significant difference in the true/false question scores as measure by the cell knowledge test pre and post activity: $t(19)=-6.64$, $p < .001$. Means are shown in the table below.

Means for pre and post test scores:

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Pre score	6.10	20	1.80	.40
	Post score	9.00	20	1.86	.42

Correlations between fine dexterity and score difference (pre to post).

A Pearson's correlation found that there was a significant correlation between the tweezer dexterity and the score difference (pre/post-test): $r(18)=.49$, $p=.03$. Therefore, there was a positive association between fine dexterity score (tweezer) and differences in score from pre to post-test.

However, no correlation between score difference and finger dexterity ($r(20)=.06$, $p=.80$) or score difference and the dexterity sum (sum of both finger and tweezer scores): $r(20)=.37$, $p=.11$.

Correlations between spatial ability and score difference

A Spearman's Rho correlation showed that there was no correlation between spatial ability (BDT or SRT or the sum of both tests) with score difference (pre/post-test), as shown in the table below.

Correlations

			Score_difference	BDT	SRT	Spatial_Sum
Spearman's rho	Score_difference	Correlation Coefficient	1.000	.367	.134	.351
		Sig. (2-tailed)	.	.111	.572	.130
		N	20	20	20	20
	BDT	Correlation Coefficient	.367	1.000	.657**	.972**
		Sig. (2-tailed)	.111	.	.000	.000
		N	20	24	24	24
	SRT	Correlation Coefficient	.134	.657**	1.000	.793**
		Sig. (2-tailed)	.572	.000	.	.000
		N	20	24	24	24
	Spatial_Sum	Correlation Coefficient	.351	.972**	.793**	1.000
		Sig. (2-tailed)	.130	.000	.000	.
		N	20	24	24	24

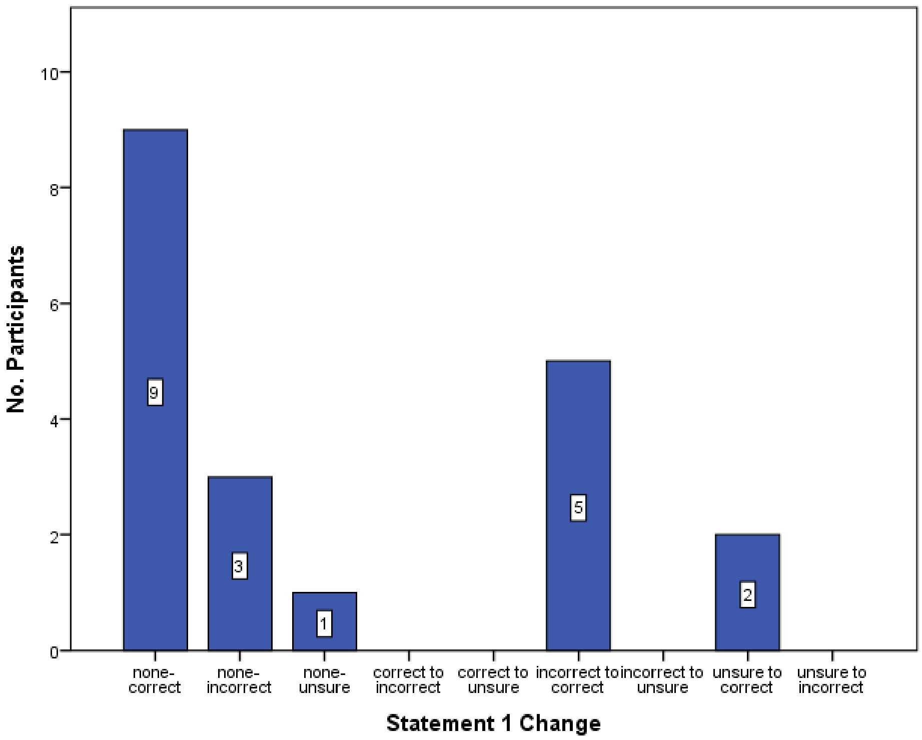
**. Correlation is significant at the 0.01 level (2-tailed).

Changes in answers for the true/false/unsure section of the test

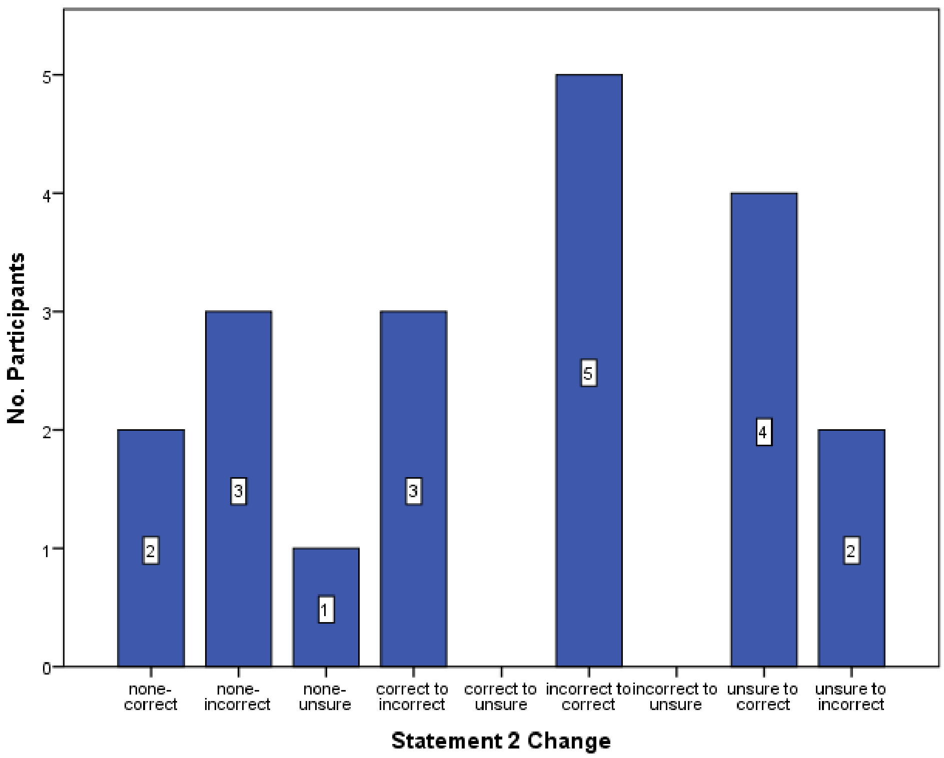
The following graphs depict the change in answers from pre to post test for the true/false/unsure section of the cell knowledge test.

Answer changes for each statement

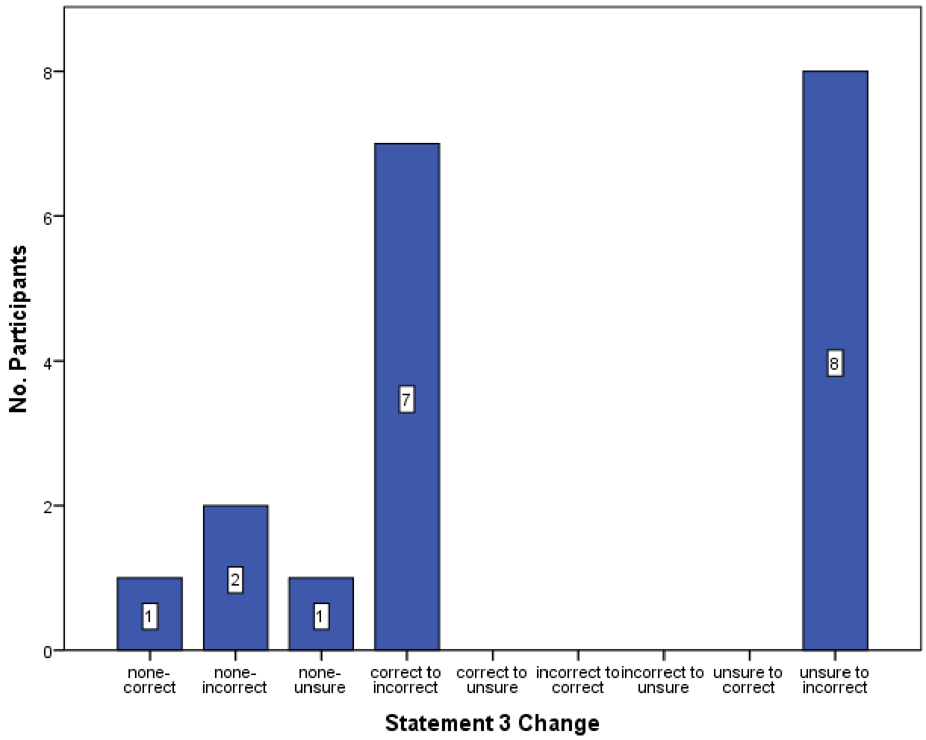
Statement 1: The plasma membrane is a barrier that stops everything from entering/exiting the cell



Statement 2: The plasma membrane is solid

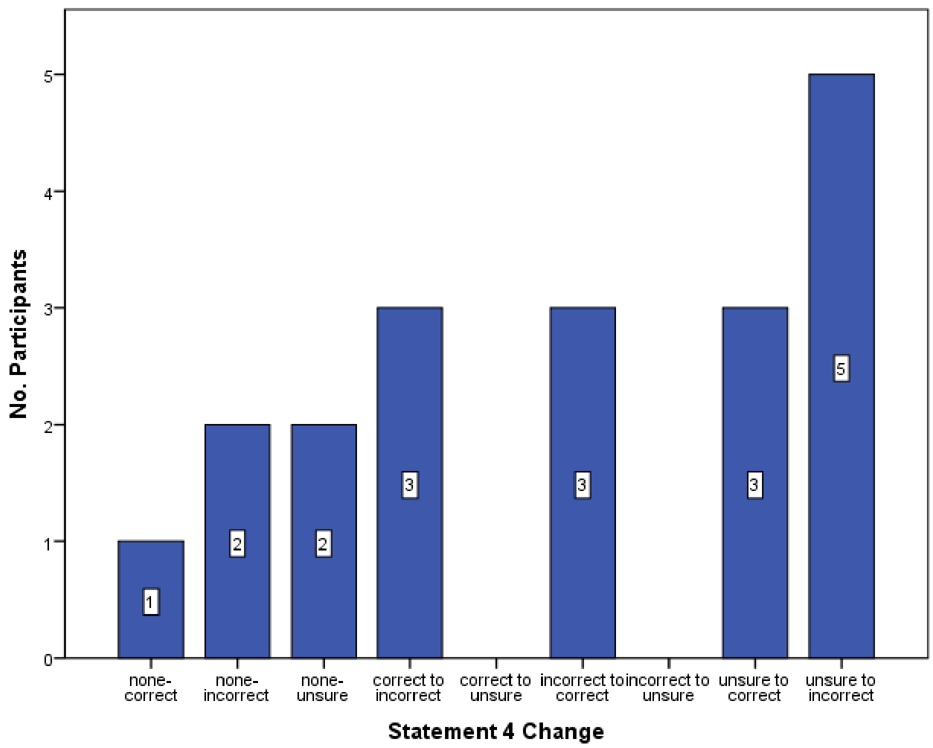


Statement 3: The plasma membrane is transparent



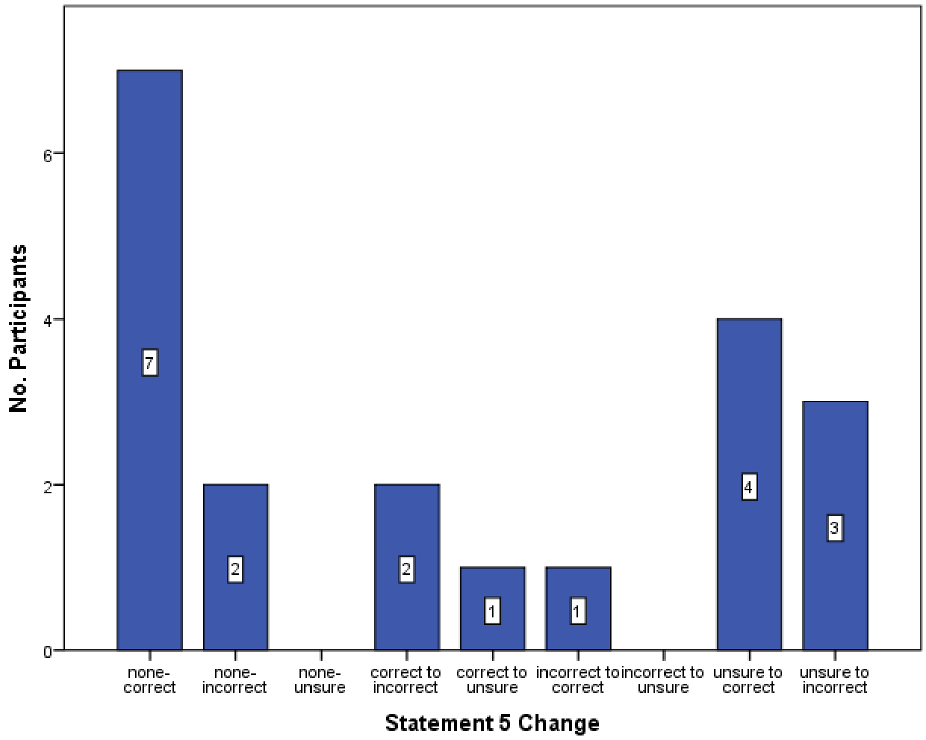
It is possible that there is misunderstanding for this statement.

Statement 4: The plasma membrane contains membrane proteins that sit in a fixed position in the membrane



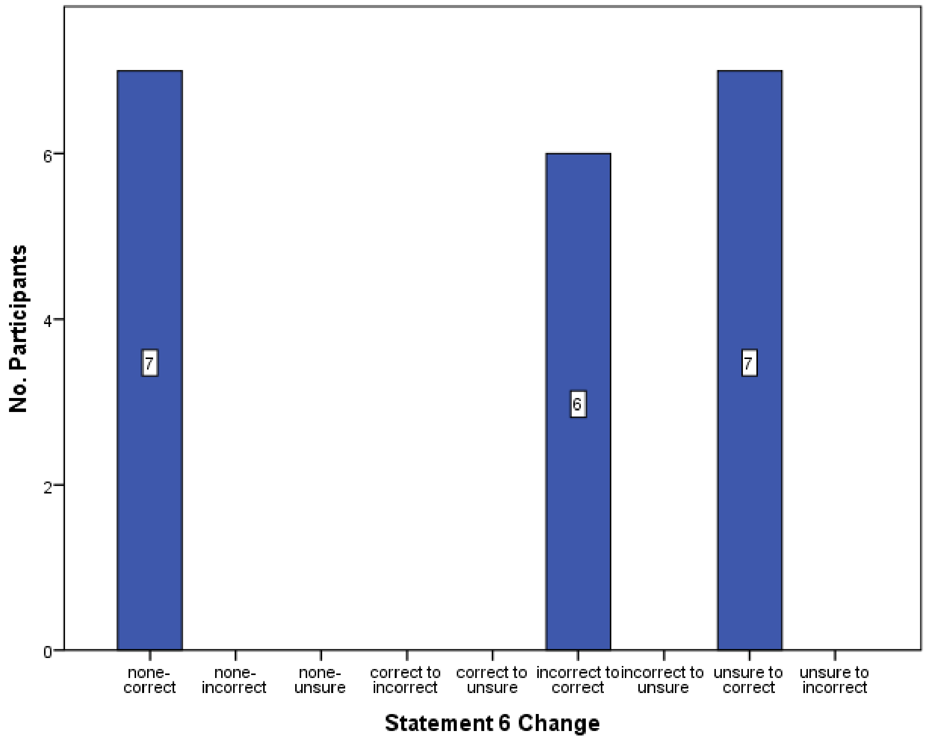
Mixed results may indicate confusion for this topic

Statement 5: All membrane proteins are the same, forming channels that allow anything to cross the membrane and enter the cell



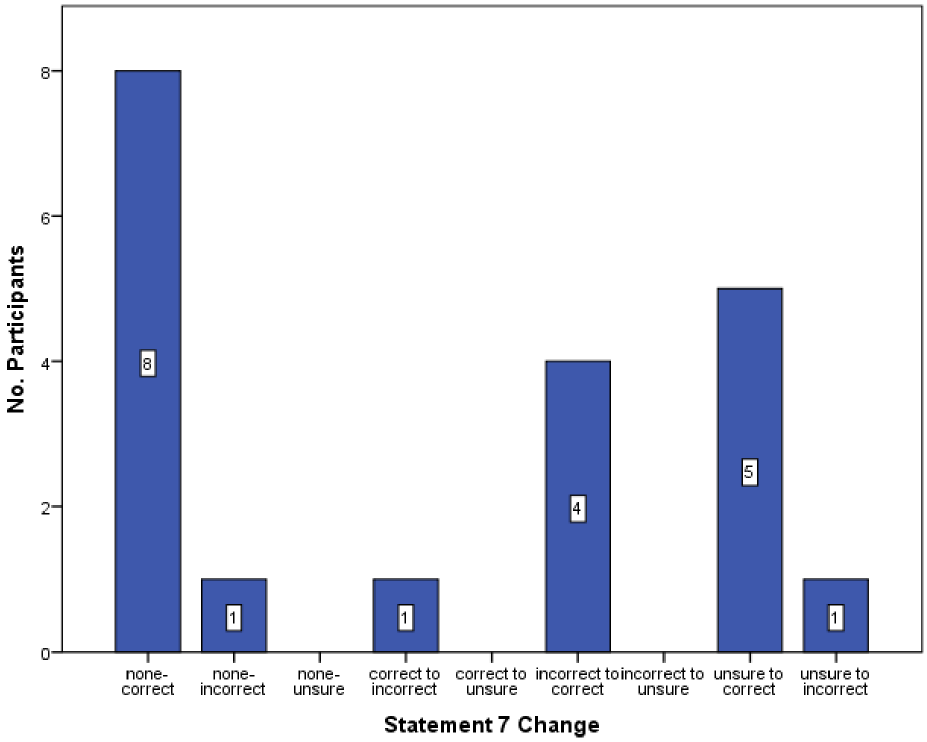
Mostly correct pre and post.

Statement 6: Oxygen can freely enter and exit a cell (does not need a channel)



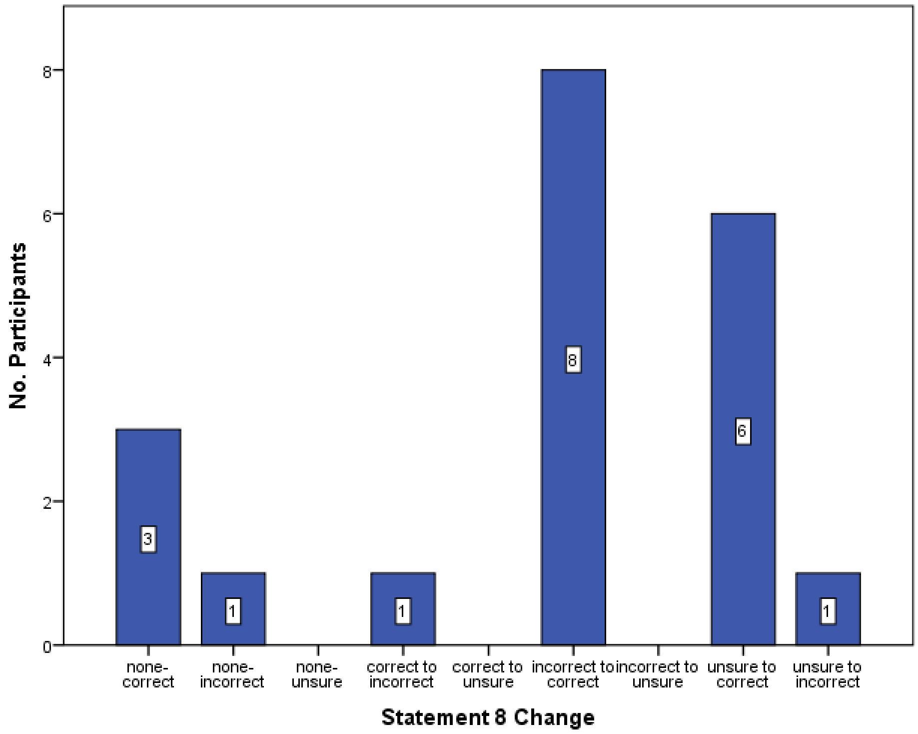
Mostly all correct at pre to changes to correct, which shows understanding and correction of misunderstandings.

Statement 7: Glucose can freely enter and exit a cell (does not need a channel)



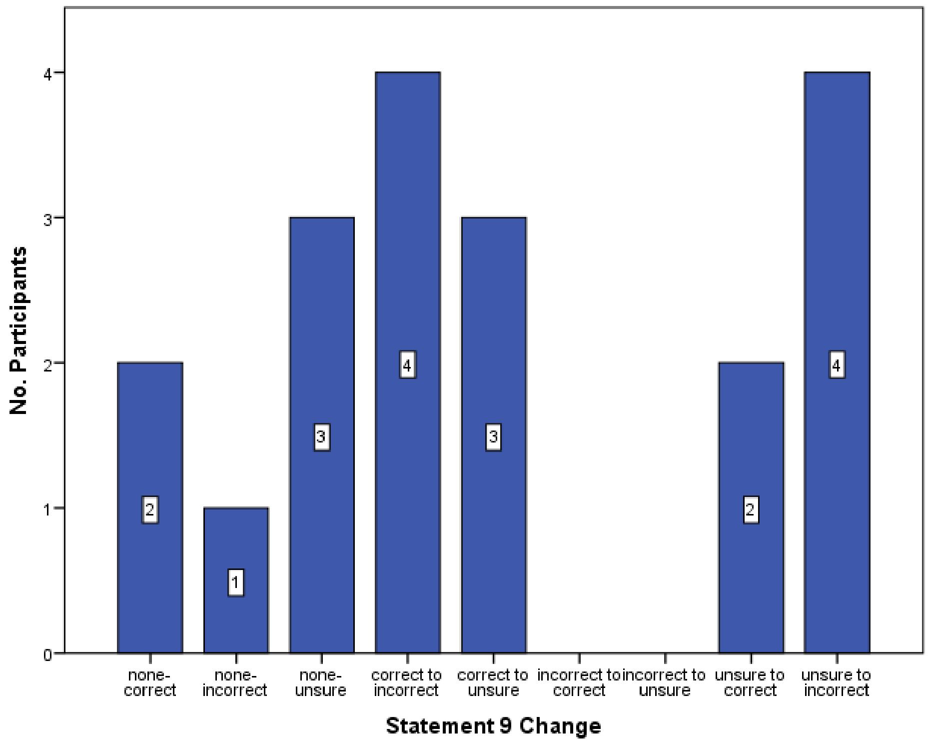
General shift to correct or always correct

Statement 8: Carbon dioxide can freely enter and exit a cell (does not need a channel)

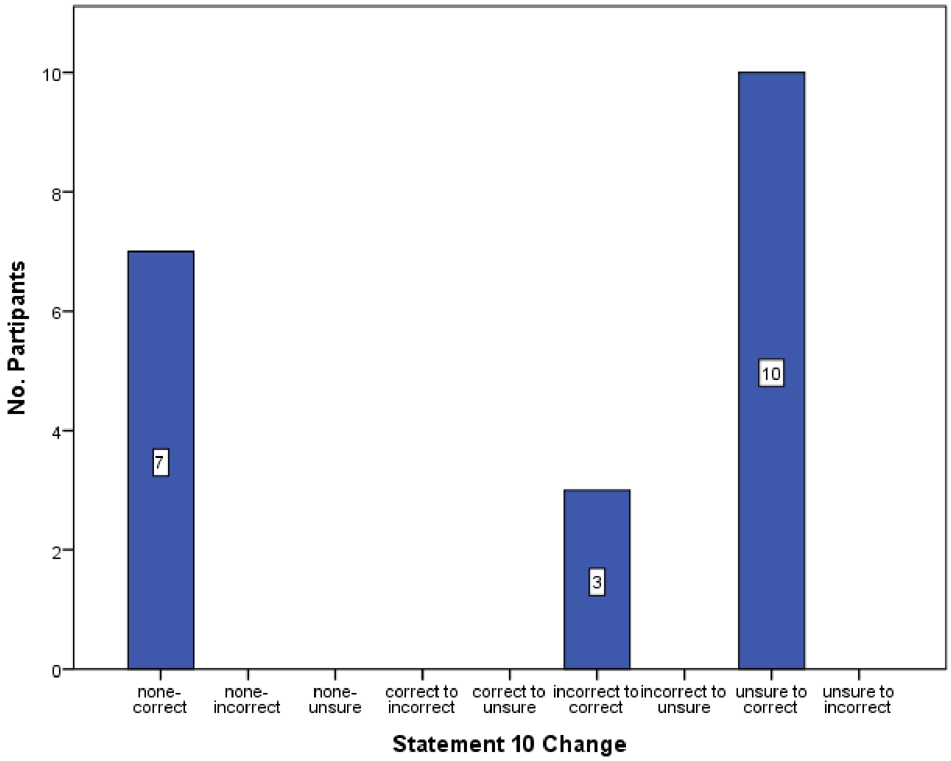


Shift to correct as there fewer people scoring correct before

Statement 9: Sodium can freely enter and exit a cell (does not need a channel)

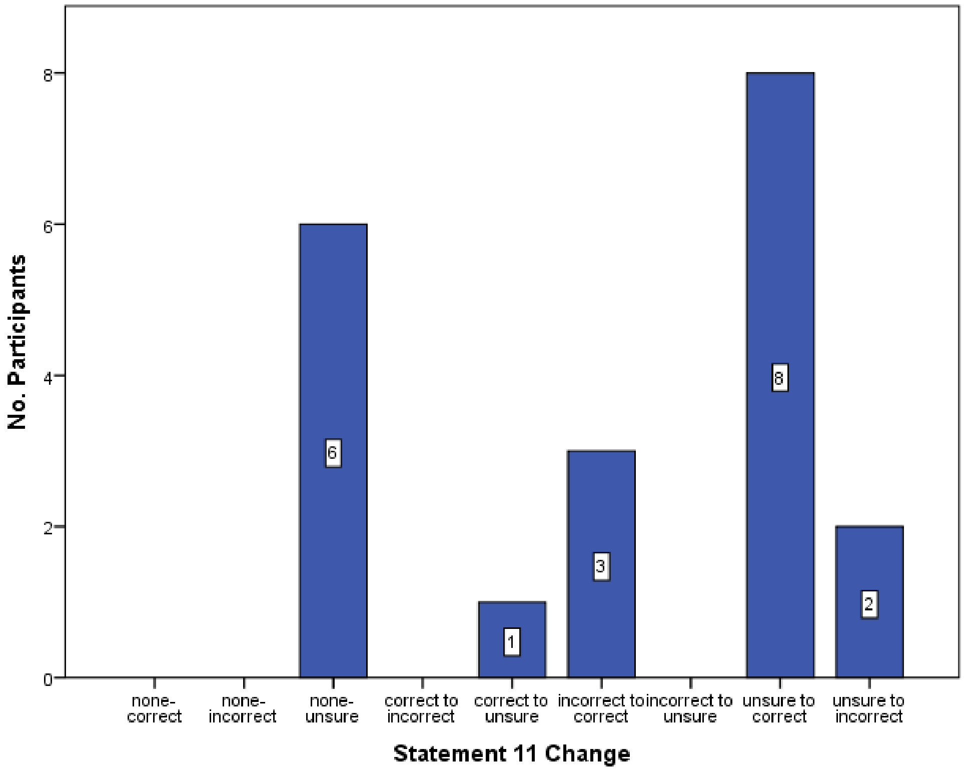


Statement 10: Glucose is smaller than oxygen



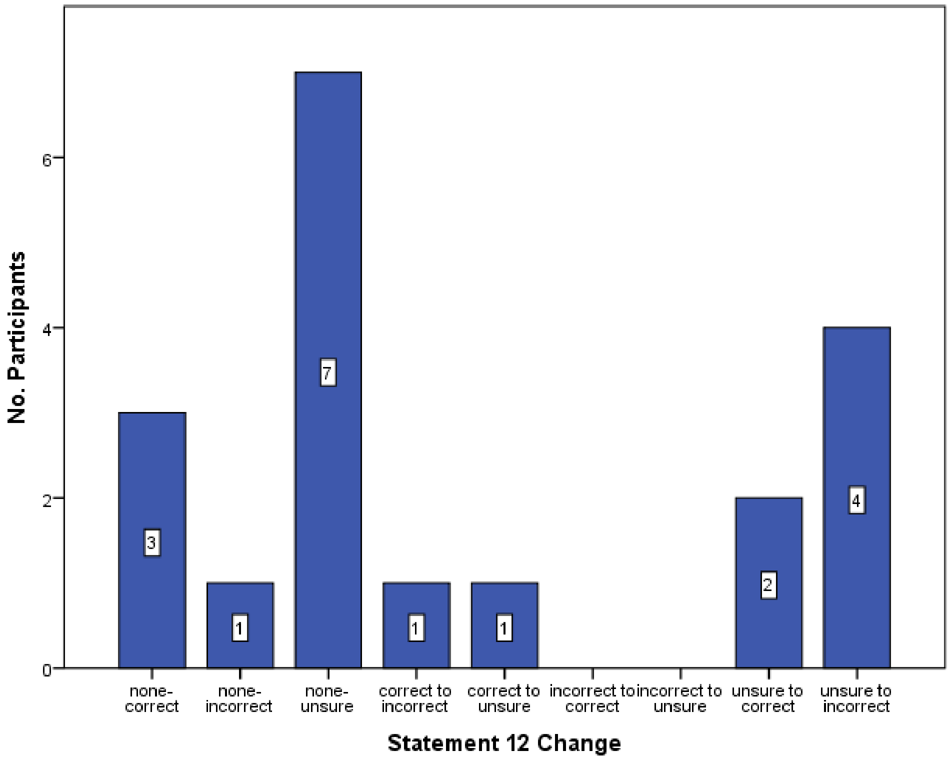
Shift from unsure and incorrect to correct.

Statement 11: The plasma membrane contains about 20 glucose channels

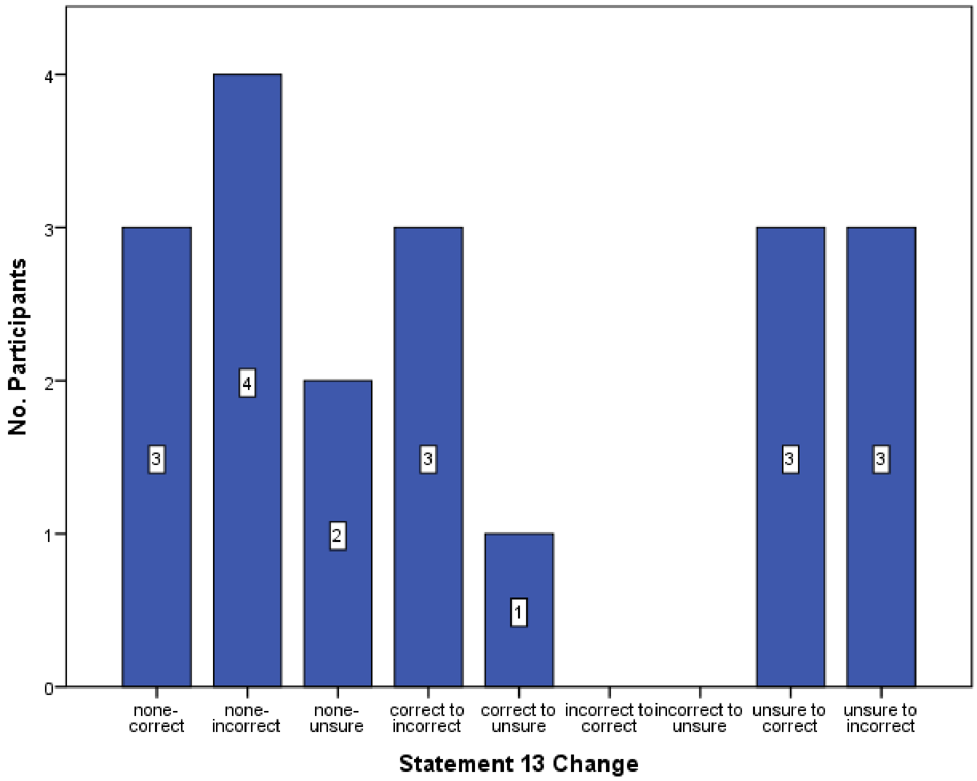


Shift to correct but many unsure still.

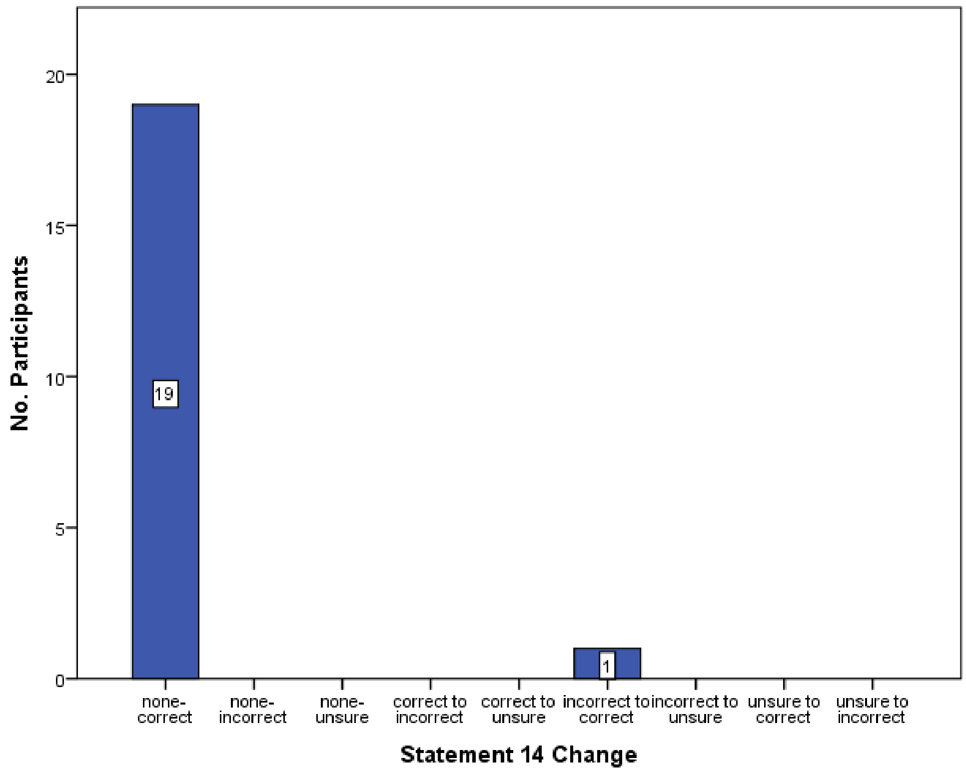
Statement 12: If there is an equal amount of oxygen inside and outside the cell it will be harder for more oxygen to enter than if there is more oxygen outside



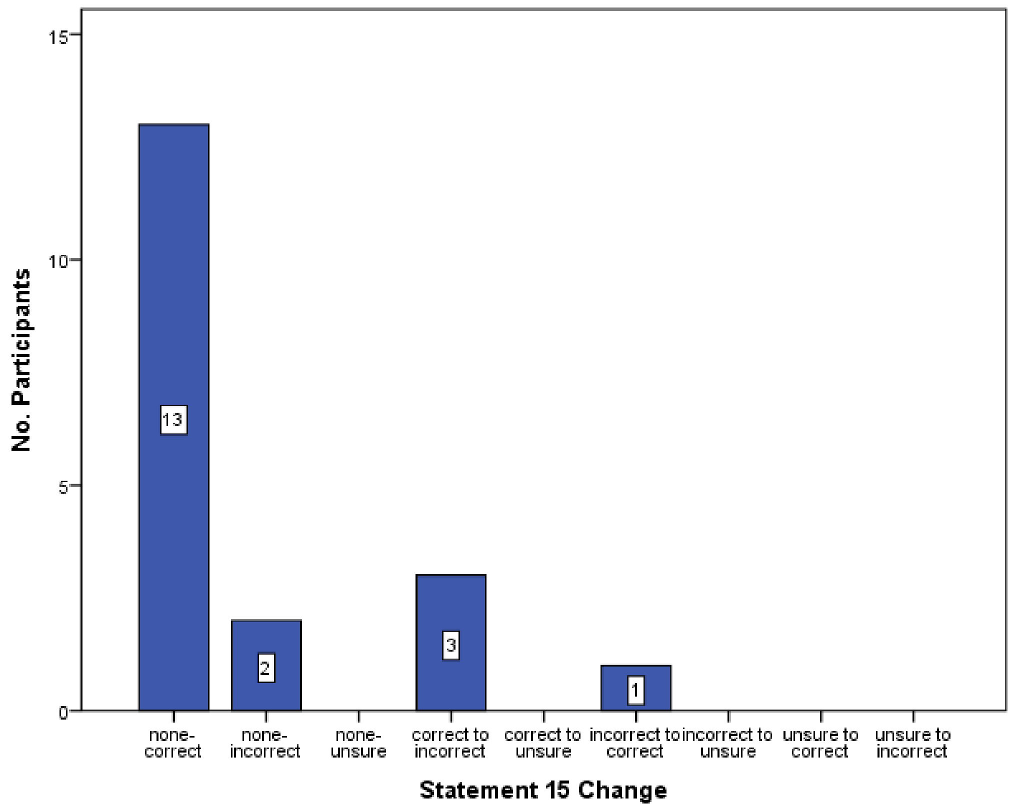
Statement 13: The amount of glucose inside a cell makes no difference to how easy it is for glucose to enter



Statement 14: During aerobic respiration a cell uses oxygen and glucose



Statement 15: During aerobic respiration a cell produces oxygen and water

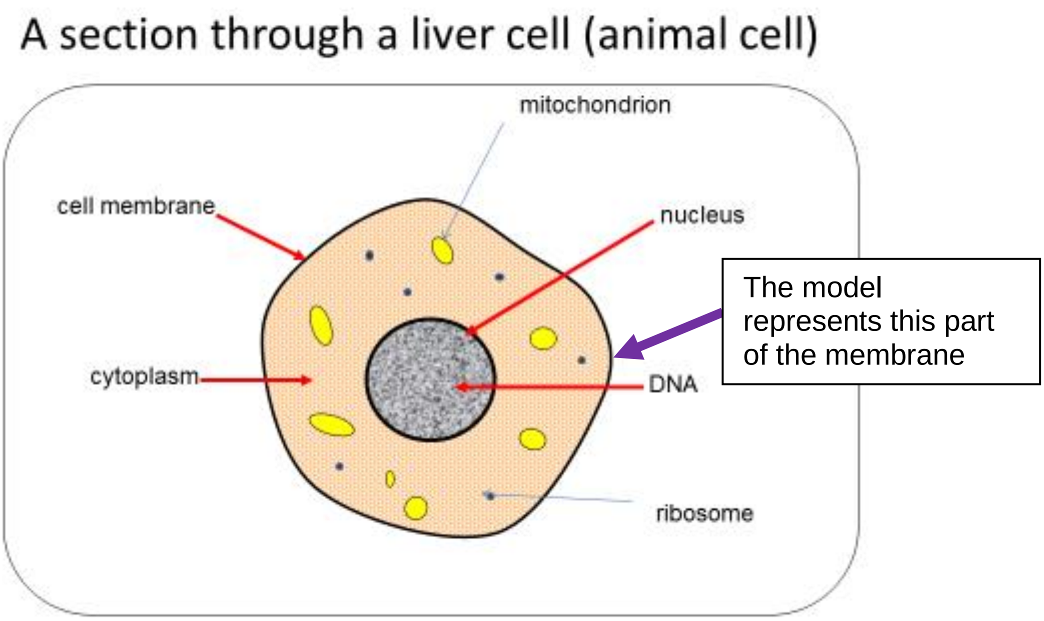


7.25 Appendix Y: Worksheet for Pilot 5

Interacting with a cell membrane model using a haptic device

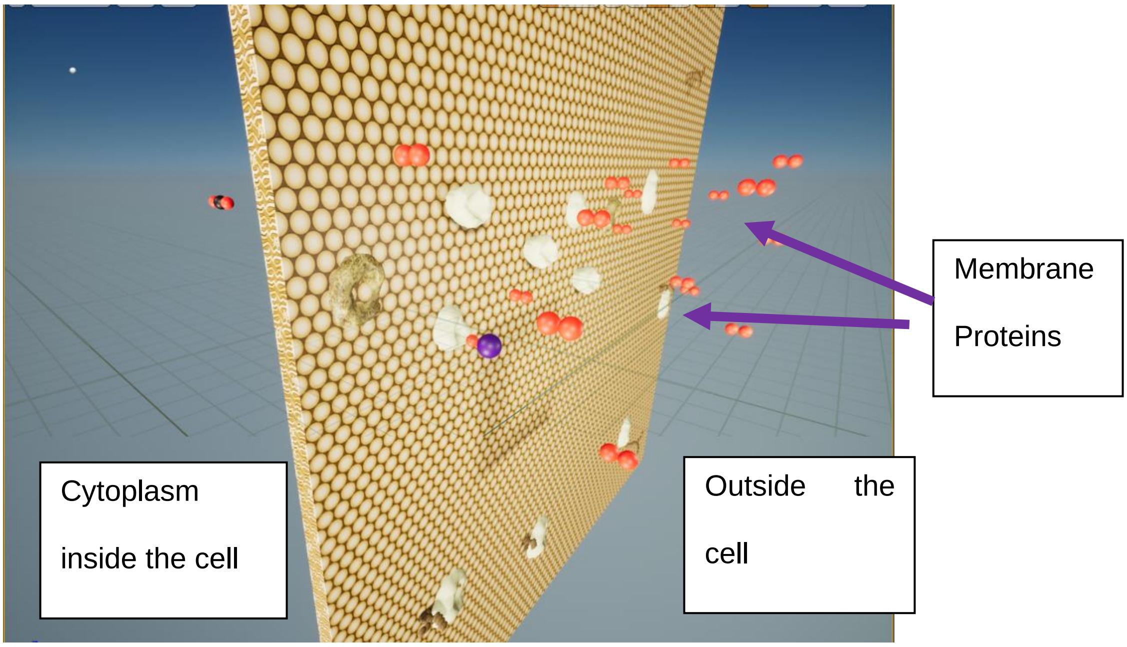
Instructions -read these instructions before you start the tasks

Look at the diagram below to remind yourselves of the cell structure as seen in two dimensions.



In the model you will see the detail of a small section of the membrane in 3D. There is a label to show which side of the membrane you would find the cytoplasm

A screen shot of part of the model



You will work in pairs and discuss your answers. You will take turns being the ‘pilot’ and the ‘co-pilot’.

The pilot will wear the headset that allows you to see the 3D cell membrane model and control the haptic device that allows you to manipulate the model.

The co-pilot is responsible for making sure you complete the tasks quickly and efficiently so the co-pilot will read and explain the worksheet instructions, operate the software and help the pilot achieve the task goals by discussing the questions and answers and write the answers on the sheet.

After Task 1 the pilot and co-pilot will switch roles for Task 2.

Please refer to the instruction sheet for how to use the software.

Task 1: Investigating the cell membrane – membrane permeability

Cells are surrounded by a membrane that controls what can enter and exit the cell. Explore the cell membrane model thinking about how it feels and looks

11. Try to describe what you think the parts of the model feel like.

----

12. Proteins float in the membrane, like icebergs. Can you move a membrane protein around? Try to describe how you think it feels.

Particles are moving around both in the cytoplasm and outside the cell.

13. Co-pilot -freeze the model so that the particles stop moving. Pilot try to grab hold of an oxygen molecule and move it into the cell. Note that if you touch a molecule its name label will appear. Now try moving an oxygen molecule out of the cell. Try to describe what you think you feel as you move the oxygen molecule into and out of the cell.

----

14. Now try to touch and grab hold of a carbon dioxide molecule and move it into the cell. Now try moving a carbon dioxide molecule out of the cell. Try to describe what you think you feel as you move the carbon dioxide molecule into and out of the cell.

----

15. Co-pilot -Set the model to slow motion. Pilot – Try to touch or grab the particles and follow their movement. Try to describe what you think you feel and observe

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----

16. Co-pilot -freeze the model again. Both of you think and discuss – If there were more oxygen molecules outside the cell what do you think would happen to the movement of molecules across the membrane? Why?

----

17. Try adding more oxygen or carbon dioxide to the model (Co-pilot to add at least 10 more). Try to move all the oxygen molecules to the inside of the cell. Try to explain what you think you feel and observe. Was your idea in Question 6 correct?

----

18. Don't unfreeze it yet but what do you think will happen if you unfreeze the model?

----

19. Co-pilot to set the model to slow motion. Watch and note what happens and try to explain why.

Swap over with your partner now so that you each get a turn at being pilot and co-pilot. Ask the instructor to set up the model at the next level for Task 2.

Task 2: Movement across the cell membrane – Membrane channels

In the previous level the model was more simplified – now you can see more particles and more of the complexity of the membrane. Choose slow motion.

20. Touch or grab the particles and identify them– fill in the table below

	Colour	Size (Order 1-5) 1 is smallest
Oxygen molecule:		
Carbon dioxide molecule:		
Glucose molecule:		
Sodium ion:		
Potassium ion:		

21. Co-pilot freeze the model. Pilot try to grab hold of a glucose molecule and move it from the outside of the cell into the cytoplasm. Try to describe what you think you feel as you move the glucose molecule into the cell (clue: glucose has to go into the cell because it is needed for respiration – but how does it get in?)

----

22. Add more glucose to the fluid surrounding the cell (Co-pilot to press the buttons to add at least 10 more) (this simulates the effect of glucose moving from the bloodstream to the tissues). Now try again moving glucose molecules into the cell and away from the membrane into the cytoplasm. What do you think you feel and observe?

----

23. Can you think of an explanation for the movement of glucose into and out of the cell in this model?

----

24. In freeze mode – Try experimenting further with adding glucose to the inside or outside of the cell and moving the glucose molecules into and out of the cell to test your explanation. Note your observations.

----

25. Turn slow motion on. What do you notice? Compare and contrast the movement of glucose and oxygen across the membrane and into the cell.

----

26. Try to summarise in a list what you have found out about membrane proteins, the movement of oxygen, carbon dioxide and glucose across the cell membrane and explain why this movement is important for cells.

Task 3 Extension if you have time

27. In addition to glucose, carbon dioxide and oxygen there are other particles in this model. Explore their movement with the haptic device and make notes on what you find and try to explain your observations.

7.26 Appendix Z: Ethical approval for Pilot 5

Research Ethics Office
King's College London
Rm 5.11 FWB (Waterloo Bridge Wing)
London
SE1 9NH

05 October 2017
TO: Megan Tracey
SUBJECT: Confirmation of Minimal Risk Registration for 'Using Haptics to Improve Understanding in Cell Biology- PGCE biology focus group'

Dear Megan

Thank you for submitting your Research Ethics Minimal Risk Registration Form. This letter acknowledges the receipt of your registration; your Research Ethics Number is **MR/17/18-43**. You may begin collecting data immediately.

Be sure to keep a record your registration number and include it in any materials associated with this research. Registration is valid for **one year** from today's date. Please note it is the responsibility of the researcher to ensure that any other permissions or approvals (i.e. R&D, gatekeepers, etc.) relevant to their research are in place, prior to conducting the research.

Record Keeping:
In addition, you are expected to keep records of your process of informed consent and the dates and relevant details of research covered by this application. For example, depending on the type of research that you are doing, you might keep:

- A record of the relevant details for public talks that you attend, the websites that visit, the interviews that you conduct
- The 'script' that you use to inform possible participants about what your research involves. This may include written information sheets, or the generic information you include in the emails you write to possible participants, or what you say to people when you approach them on the street for a survey, or the introductory material stated at the top of your on-line survey.
- Where appropriate, records of consent, e.g. copies of signed consent forms or emails where participants agree to be interviewed.

Audit:
You may be selected for an audit, to see how researchers are implementing this process. If audited, you will be expected to explain how your research abides by the general principles of ethical research. In particular, you will be expected to provide a general summary of your review of the possible risks involved in your research, as well as to provide basic research records (as above in Record Keeping) and to describe the process by which participants agreed to participate in your research.

Remember that if you have any questions about the ethical conduct of your research at any point, you should contact your supervisor, the Research Ethics office, or a member of your Department's Research Ethics Panel for advice.

Feedback:
If you wish to provide any feedback on the process you may do so by emailing crec-minrisk@kcl.ac.uk .

We wish you every success with this work.

With best wishes
Research Ethics Office

7.27 Appendix AA: Information sheets for Pilot 5

INFORMATION SHEET FOR PARTICIPANTS

REC Reference Number: **MR/17/18-43**

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title

Using Haptics to Increase Understanding in Cell Biology

Invitation Paragraph

We would like to invite you to take part in this research. Choosing not to take part is completely voluntary, will not disadvantage you in anyway and will have no effect on your course. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

Overall, we would like to develop a 3D learning environment with visual and touch (haptic) feedback that encourages co-operation and allows students to hypothesise and explore scientific concepts.

We would like for you to have the opportunity to use the haptic learning system we intend to use with students, which provides a virtual 3D cell membrane which students can view and manipulate. Afterwards, some of you will be asked to take part in a focus group where we will ask about your opinions about the system and your insights regarding its usefulness in biology education.

Why have I been invited to take part?

We are inviting all students in your cohort to take part.

Do I have to take part?

Participation is voluntary. You should read this information sheet and if you have any questions you should ask the research team.

What will happen to me if I take part?

If you decide to take part, you will be given a consent form to indicate your willingness to participate in the study and agree to the use of your anonymised data. Even if you have decided to take part, you are still free to withdraw at any time without giving a reason.

After expressing your consent, you will take part in the learning activity. In pairs, you will take turns being the 'pilot' and the 'co-pilot'. The pilot will wear the oculus rift viewer showing the cell membrane model and use 3D haptic device to manipulate the cell. The co-pilot will be in control of the worksheet instructions and help the pilot achieve the task goals and identify features by being able to view the membrane model on the computer screen.

Once the activity is complete, you may be asked to join a focus group to share your views. This will take 30 minutes and will be audio recorded.

This will be the end of the study. In the event of you wishing to withdraw from the study after submitting your data, you will still be able to do so up to 01/11/17, and any notes and recordings of your interaction with the system can be removed. If you are involved in the focus group however, unfortunately your comments will not be identifiable and cannot be extracted and removed from the recording.

<u>What are the possible benefits and risks of taking part?</u>

There are no foreseeable risks in participating in the study. The study will give you the opportunity to experience new technology which may help students in their learning.

<u>Will my taking part be kept confidential?</u>

The information you provide will be treated with the strictest confidentiality and will be held securely until the research is finished. The data for analysis will be anonymised and your real name will never be used. It will not possible to identify you individually from any reports and papers that are written. There will be no possibility of you as individuals being linked with the data.

The UK Data Protection Act 1998 will apply to all information gathered within the interviews and held on password-locked computers and encrypted hard drives.

<u>What will happen to the results of the study?</u>

The results of this study will be analysed to gather insights into the systems development and perceived usefulness in the classroom. The results may also be reported through publications in the field of Educational research.

<u>Who should I contact for further information?</u>

If you have any questions or require more information about this study, please contact me using the following contact details:

Researcher name: Megan Tracey
Researcher Email: megan.tracey@kcl.ac.uk

What if I have further questions, or if something goes wrong?

If this study has harmed you in any way or if you wish to make a complaint about the conduct of the study you can contact King's College London using the details below for further advice and information:

Research Supervisor: Dr. Mary Webb
Supervisor email: mary.webb@kcl.ac.uk

Supervisor Address: Dr Mary Webb
School of Education, Communication and Society
Waterloo Bridge Wing
Franklin-Wilkins Building
Waterloo Road
London
SE1 9NH

Thank you for reading this information sheet and for considering taking part in this research.

7.28 Appendix BB: Consent forms for Pilot 5

CONSENT FORM FOR PARTICIPANTS IN RESEARCH STUDIES

[redacted]

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study:

Using Haptics to Increase Understanding in Cell Biology

King's College Research Ethics Committee Ref: MR/17/18-43

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Please tick

I confirm that I understand that by ticking/initialling each box I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes mean that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element I may be deemed ineligible for the study. ☐

Please tick

1. I confirm that I have read and understood the information sheet for the above study. I have had the opportunity to consider the information and asked questions which have been answered satisfactorily. ☐

2. I understand that my participation is voluntary, that I am free to withdraw at any time without giving any reason, and that doing so will have no effect on grades or schoolwork. Furthermore, I understand that I will be able to withdraw my data up to 01/11/17. ☐

3. I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998.

4. I understand that my information may be subject to review by responsible individuals from the College for monitoring and audit purposes.

5. I understand that confidentiality and anonymity will be maintained, and it will not be possible to identify me in any publications.

6. I agree that the research team may use my data for future research and understand that any such use of identifiable data would be reviewed and approved by a research ethics committee.

7. I understand that the information I have submitted will be published as a report and I wish to receive a copy of it.

8. I consent to being audio/video recorded.

9. I consent that my audio/video may be used at public events, such as academic conferences.

Name of Participant	Date	Signature
Name of Researcher	Date	Signature

7.29 Appendix CC: Focus group questions for Pilot 5

Questions for Focus Group Meeting with Biology PGCE Trainee Teachers

The System

1. How easy did you find the VR system to use?

2. Was there anything you particularly liked about the VR system? Why?

3. What would you change about the VR system? Why?

4. In this activity, you worked in a pair. How easy was it to work collaboratively whilst using the VR system?

Learning

Thinking about your own previous experience of learning about cell biology at various levels as well as your developing experience of teaching

5. What particular problems do you think people have when learning cell biology?

6. What do you think might be the benefits for Year 8 students of using a system like this to learn cell biology?

7. Do you think being able to "feel" the membrane and particles virtually can help learners to learn better? Why?

8. What do you think were the advantages of working together in pairs?

9. Any other comments?

7.30 Appendix DD: Main Study Worksheet

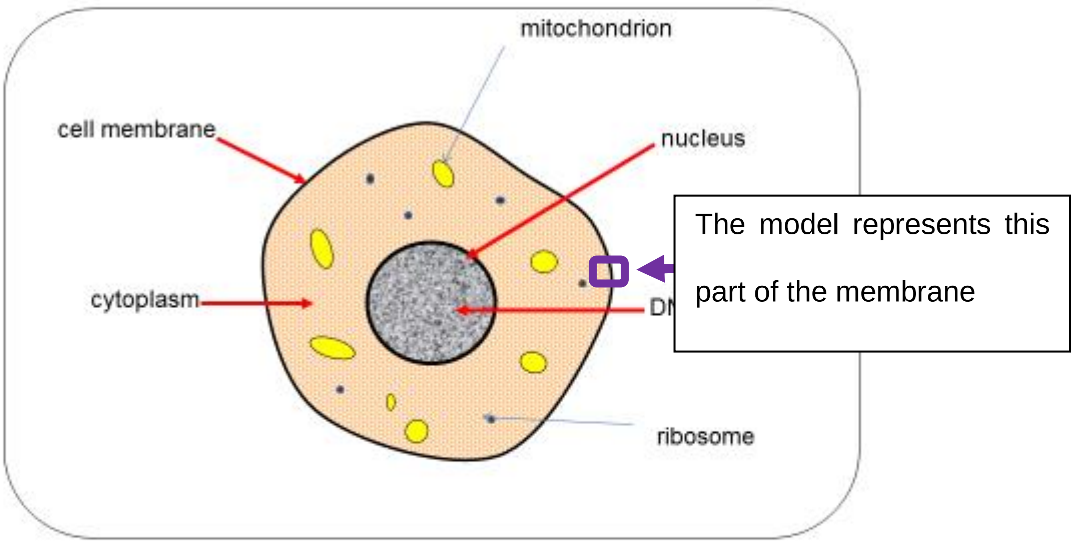
Interacting with a cell membrane model using a haptic device

Introduction

BOTH READ THIS INTRODUCTION BEFORE YOU START THE TASKS

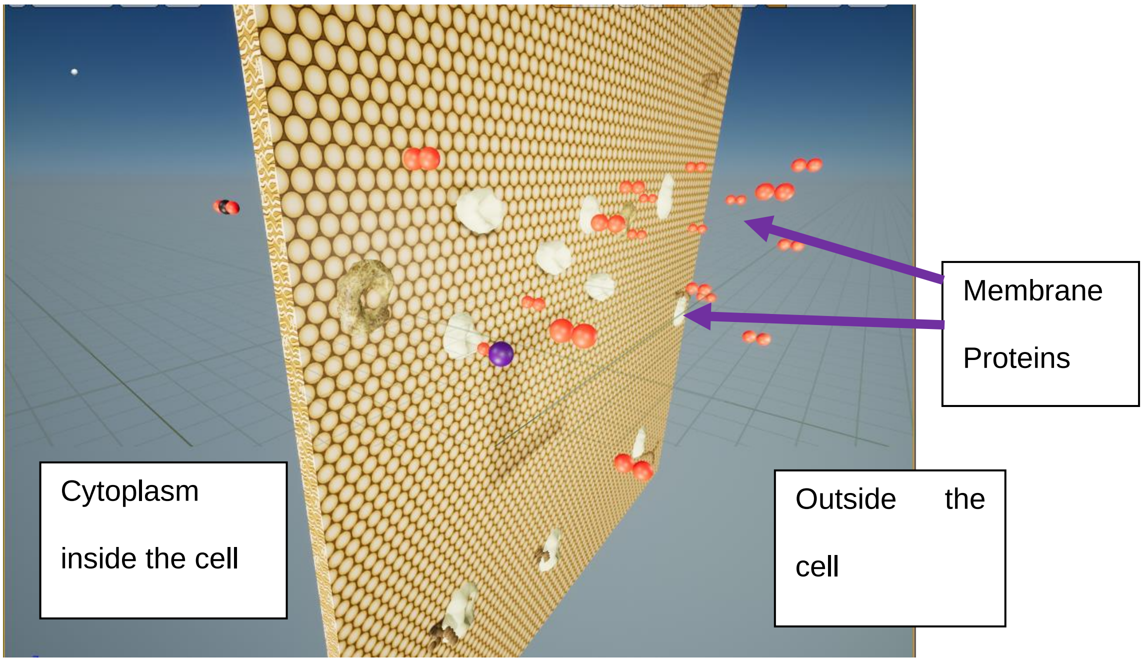
Look at the diagram below to remind yourselves of the cell structure as seen in two dimensions.

A section through a liver cell (animal cell)



Cells are surrounded by a membrane that controls what can enter and exit the cell. In the model you will see the detail of a small section of the membrane in 3D. There is a label to show which side of the membrane you would find the cytoplasm

A screen shot of part of the model



You will work in pairs and discuss your answers. You will take turns being the 'pilot' and the 'co-pilot'.

The pilot will wear the headset that allows you to see the 3D cell membrane model and control the haptic device that allows you to interact with the model.

The co-pilot is responsible for making sure you complete the tasks efficiently so the co-pilot will:

- read and explain the worksheet instructions
- operate the software and help the pilot achieve the task goals, by discussing the questions and answers
- write the answers on the sheet.

After Task 1 the pilot and co-pilot will switch roles for Task 2.

Co-pilot -Please refer to the **software instruction sheet** for how to use the software.

Task 1: Investigating the cell membrane – membrane permeability

The model speed is set to **fast motion**

1. Pilot -try to describe what you think you can feel of the parts of the model as you explore the model using the haptic device.

Co-pilot -set the model speed to **slow motion**

2. Proteins float in the membrane, like icebergs. Pilot -Try to describe what you think you feel as you move a membrane protein around.

Particles are moving around both in the cytoplasm and outside the cell.

Co-pilot -**freeze the model** so that the particles stop moving.

3. Pilot -Try to describe what you think you feel as you move a carbon dioxide molecule out of the cell and then back into the cell. Note that if you touch a particle its name label will appear.

----

4. Both of you think and discuss – If there were more carbon dioxide molecules inside the cell than outside what do you think would happen to the movement of molecules across the membrane? Why?

----

5. Co-pilot -Add more oxygen and carbon dioxide to the model (add at least 10 more molecules). Try to explain what you think you feel and observe as you try to move all the carbon dioxide molecules to the outside of the cell. Was your idea in Question 4 correct?

----

6. Don't unfreeze it yet but what do you think will happen to the distribution of the molecules if you unfreeze the model?

Co-pilot -set the model speed to **slow motion**

7. Watch and note what happens and try to explain why.

Swap over with your partner now so that you each get a turn at being pilot and co-pilot. Ask the instructor to set up the model at the next level for Task 2.

Task 2: Movement across the cell membrane – Membrane channels

In the previous level the model was more simplified – now you can see more particles and more of the complexity of the membrane.

Co-pilot -check that the model speed is set to **slow motion**

8. Touch or grab the particles and identify them– fill in the table below

	Colour	Size (Order 1-5) 1 is smallest
Oxygen molecule:		
Carbon dioxide molecule:		
Glucose molecule:		
Sodium ion:		
Potassium ion:		

Co-pilot -**freeze the model**.

9. Pilot -try to describe what you think you feel as you move a glucose molecule from the outside of the cell into the cytoplasm (glucose must go into the cell because it is needed– but how does it get in?)

Co-pilot -add at least 10 more glucose molecules to the fluid surrounding the cell

10. What do you think you feel and observe as you move glucose molecules into the cell and away from the membrane into the cytoplasm?

----

11. Can you think of an explanation for the movement of glucose into and out of the cell in this model?

----

12. In **freeze mode** – Try experimenting further with adding glucose to the inside or outside of the cell and moving the glucose molecules into and out of the cell to test your explanation. Note your observations.

----

13. In **slow motion** mode. What do you notice about the movement of molecules? Compare and contrast the movement of glucose and oxygen across the membrane and into the cell.

----

14. Try to summarise in a list what you have found out about membrane proteins, the movement of oxygen, carbon dioxide and glucose across the cell membrane and explain why this movement is important for cells.

Task 3 Extension if you have time

15. In addition to glucose, carbon dioxide and oxygen there are other particles in this model. Explore their movement with the haptic device and make notes on what you find and try to explain your observations.

7.31 Appendix EE: Table demonstrating each assessment item, corresponding biological concepts/misconceptions, whether they are addressed equally in all conditions, and why according to theory.

				Addressing the concept/misconception in relation to theory		
Assessment Items:	**Corresponding concepts**	**Misconceptions related to these concepts (Chapter 2)**	**Addressed equally in haptic/non-haptic condition?**	**DCT**	**CLT**	**Embodied Cognition**
Q3 Statement 1: The cell membrane is a barrier that stops everything from entering /leaving the cell.	Selective permeability of the membrane (Dreyfus & Jungwirth, 1989; Flores et al., 2003; Malinska 2014). Mechanisms of selective permeability (Dreyfus & Jungwirth, 1989).	Only liquid materials can pass through the membrane (Dreyfus & Jungwirth, 1989). The cell 'knows' what materials to accept and which to reject (Dreyfus & Jungwirth, 1989). The cell takes in only	No. Additional information provided in the haptic condition.	The haptic condition allows the combined coding of visual and haptic information, which DCT suggests is beneficial.	The haptic condition allows the use of multiple processing channels, which CLT suggests can lower cognitive load.	The haptic condition provides more opportunities for embodied experiences and is therefore beneficial according to Embodied Cognition.

		those molecules which it 'needs' (Dreyfus & Jungwirth, 1989). Cells take what they need from the environment (Flores et al., 2003).				
Q3 Statement 2: The cell membrane is fluid.	Fluid structure of the membrane (Storey, 1990)	The cell membrane is a static rather than a fluid system (Storey, 1990).	Not addressed in either condition.	N/A	N/A	N/A
Q3 Statement 3: The cell membrane contains membrane proteins that sit	Fluid structure of the membrane (Storey, 1990) Mechanisms of selective permeability	The cell membrane is a static rather than a fluid system (Storey, 1990).	<u>Fluid structure of the membrane:</u> Not addressed in either condition.	The haptic condition allows the combined coding of visual and haptic information,	The haptic condition allows the use of multiple processing channels, which	The haptic condition provides more opportunities for embodied experiences and

in a fixed position in the membrane.	(Dreyfus & Jungwirth, 1989).		<u>Mechanisms of selective permeability:</u> No. Additional information provided in the haptic condition.	which DCT suggests is beneficial.	CLT suggests can lower cognitive load.	is therefore beneficial according to Embodied Cognition.
Q3 Statement 4: All membrane proteins form channels that allow anything to cross the membrane and enter the cell.	Mechanisms of selective permeability (Dreyfus & Jungwirth, 1989). Selective permeability of the membrane (Dreyfus & Jungwirth, 1989; Flores et al.,	Only liquid materials can pass through the membrane (Dreyfus & Jungwirth, 1989). The cell 'knows' what materials to accept and which to reject (Dreyfus & Jungwirth, 1989). The cell takes in only	No. Additional information provided in the haptic condition.	The haptic condition allows the combined coding of visual and haptic information, which DCT suggests is beneficial.	The haptic condition allows the use of multiple processing channels, which CLT suggests can lower cognitive load.	The haptic condition provides more opportunities for embodied experiences and is therefore beneficial according to

	2003; Malinska 2014).	those molecules which it 'needs' (Dreyfus & Jungwirth, 1989). Cells take what they need from the environment (Flores et al., 2003).				Embodied Cognition.
Q3 Statement 5: Oxygen can freely enter and exit a cell (does not need a channel). Q3 Statement 6: Glucose can freely enter and exit a cell (does	Selective permeability of the membrane (Dreyfus & Jungwirth, 1989; Flores et al., 2003; Malinska 2014). Mechanisms of selective permeability (Dreyfus & Jungwirth, 1989).	Only liquid materials can pass through the membrane (Dreyfus & Jungwirth, 1989). The cell 'knows' what materials to accept and which to reject (Dreyfus & Jungwirth, 1989). The cell takes in only	No. Additional information provided in the haptic condition.	The haptic condition allows the combined coding of visual and haptic information, which DCT suggests is beneficial.	The haptic condition allows the use of multiple processing channels, which CLT suggests can lower cognitive load.	The haptic condition provides more opportunities for embodied experiences and is therefore beneficial according to Embodied Cognition.

not need a channel). Q3 Statement 7: Carbon dioxide can freely enter and exit a cell (does not need a channel). Q3 Statement 8: Sodium can freely enter and exit a cell (does not need a channel).		those molecules which it 'needs' (Dreyfus & Jungwirth, 1989).				
Q3 Statement 9: An oxygen molecule is	Size and scale of micro-phenomena/ Levels of	Molecules of protein are bigger than the cell (Dreyfus & Jungwirth, 1989).	No.	The haptic condition allows the combined	The haptic condition allows the use of	The haptic condition provides more

smaller than a glucose molecule.	magnification (Tretter et al., 2006; Flores et al., 2003; Harrison and Treagust, 1996; Waldron, Spencer, and Batt, 2006; Vlaardingerbroek et al., 2014)	The size of the cell is like that of molecules and atoms (Flores et al., 2003). Atoms are made up of cells (Harrison and Treagust, 1996). Ribosomes and centrioles are visible at the same level of magnification (Vlaardingerbroek et al., 2014).	Additional information provided in the haptic condition.	coding of visual and haptic information, which DCT suggests is beneficial.	multiple processing channels, which CLT suggests can lower cognitive load.	opportunities for embodied experiences and is therefore beneficial according to Embodied Cognition.
Q3 Statement 10: The cell membrane contains about 5	Size and scale of micro-phenomena/ Levels of magnification (Tretter et al., 2006; Flores et	Molecules of proteins are bigger than the cell (Dreyfus & Jungwirth, 1989).	Yes. Addressed visually in both conditions.	Neither condition utilises multiple modalities for educational	Neither condition utilises multiple processing channels to	Neither condition provides more opportunities for embodied experiences as

glucose channels.	al., 2003; Harrison and Treagust, 1996; Waldron, Spencer, and Batt, 2006; Vlaardingerbroek et al., 2014)	The size of the cell is like that of molecules and atoms (Flores et al., 2003). Atoms are made up of cells (Harrison and Treagust, 1996). Ribosomes and centrioles are visible at the same level of magnification (Vlaardingerbroek et al., 2014).		benefit as described by DCT.	lower cognitive load and benefit learning as described by CLT.	described by embodied Cognition.
Q3 Statement 11: If there is an equal amount of oxygen inside and outside the cell it will be	Diffusion along a concentration gradient (Garvin-Doxas and Klymkowsky, 2008;	The cell takes in only those molecules which it 'needs' (Dreyfus & Jungwirth, 1989).	No. Additional information provided in the haptic condition.	The haptic condition allows the combined coding of visual and haptic information,	The haptic condition allows the use of multiple processing channels, which	The haptic condition provides more opportunities for embodied experiences and

harder for oxygen to enter than if there is more oxygen outside. Q3 Statement 12: If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside.	Friedler et al., 1987; Odom, 1995)	The cell ‘knows’ what materials to accept and which to reject (Dreyfus & Jungwirth, 1989). Cell processes are unlikely to be random due to their ‘efficient’ nature (Garvin-Doxas and Klymkowsky, 2008). Diffusion is directly driven by density gradients alone (Garvin-Doxas and Klymkowsky, 2008). Particles move because they get too crowded in one area		which DCT suggests is beneficial.	CLT suggests can lower cognitive load.	is therefore beneficial according to Embodied Cognition.

		(Odom, 1995 Odom & Kelly, 2001). Molecules spread in water because they separate into smaller particles (Odom, 1995). Particles in areas of greater concentration are more likely to bounce to other areas (Odom & Kelly, 2001). Diffusion refers only to gases (Malinska et al., 2016).				
Q3 Statement 13: During aerobic respiration a cell	Respiration (Flores et al., 2003).	Energy is yielded *by* respiration, but the cell needs energy *for* respiration (Dreyfus & Jungwirth, 1989).	N/A	N/A	N/A	N/A

uses oxygen and glucose. Q3: Statement 14: During aerobic respiration a cell produces oxygen and water.		Respiration is an exchange of gases (Flores et al., 2003).				

7.32 Appendix FF: Main Study parental consent form

LETTER OF PARENTAL CONSENT

KING'S College LONDON

Dear Parent or Guardian,

[Insert school] is currently in partnership with the University of Reading and King's College London in a research project aiming to develop new learning experiences in Science. Researchers are currently recruiting year 9 students to take part, and your child has been invited to participate.

This study will give students the opportunity to use a virtual reality learning system, which will provide a virtual 3D cell membrane with touch feedback which students can view and manipulate. We will be trialling two systems, both of which will be available for students to try. Students will work in pairs to explore the virtual 3D cell membrane and complete a worksheet encouraging discussion and co-operative learning. With their permission, students' interactions during this activity will be video recorded. In addition, students will also complete some short assessments of spatial ability, fine dexterity and their knowledge of cell biology. The session will close by asking students some questions about their experience, which will also be recorded. The entire session will last approximately 90 minutes.

Ethical approval has been granted by King's College London and the school's child protection policy will be adhered to. Participation is entirely voluntary, which will be explained to each student before the session. It will be made clear that choosing not to participate will not affect their grades or schoolwork in any way. It will also be made clear that they are free to withdraw at any time should they not wish to continue for any reason, and any data collected will be destroyed. Additionally, participants will be informed that they can withdraw their data completely up to 20/12/17.

Any information provided by the student will be treated with the strictest confidentiality and will be held securely until the research is finished. The data for analysis will be anonymised using pseudonyms. It will not possible to identify participants individually from any reports and papers that are written. There will be no possibility of participants as individuals being linked with the data.

Student will be asked for permission to video record their interactions during the activity, and also whether they consent to that material (anonymised) to be used at academic conferences in the future. Any video data will be destroyed after it has been used for research purposes and dissemination.

If you give your permission for your child to participate in this study, would you kindly complete the permission slip and return this to [insert teacher name] as soon as possible. In the meantime, should you have any questions or would like to have access to the materials used in the study, please do not hesitate to contact the research team, whose details are below.

Thanking you in advance,
Megan Tracey,
PhD Student
Email: megan.tracey@kcl.ac.uk

Research Supervisor: Dr. Mary Webb
Supervisor email: mary.webb@kcl.ac.uk

Ethics Protocol No:

Permission Slip

Name of Student:

I do/do not give my permission for my child to participate in the study.

Signature ___________________________

7.33 Appendix GG: Main Study information sheet and consent form

INFORMATION SHEET FOR PARTICIPANTS

REC Reference Number: LRS-16/17-3067

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title

Using Haptics to Increase Understanding in Cell Biology

Invitation Paragraph

We would like to invite you to take part in this research. You should only take part if you want to; choosing not to take part will not disadvantage you in anyway and will have no effect on your grades or schoolwork. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

Overall, we would like to develop a 3D learning environment with visual and touch (haptic) feedback that encourages co-operation and allows students to hypothesise and explore scientific concepts.

This study will use a haptic learning system providing a virtual 3D cell membrane which students can view and manipulate. We will be trialling two different systems, and there will be opportunities for all students to try both systems before the study ends. The study will also include some psychometric tests looking at spatial skills and fine dexterity to see whether these variables affect your interaction with the learning system.

Why have I been invited to take part?

We are inviting all Year 9 students who have yet to cover cells in their curriculum this year to take part in this study.

Do I have to take part?

Participation is voluntary. You do not have to take part. Choosing not to take part in the study will not have any effect on your schoolwork or grades. You should read this information sheet and if you have any questions you should ask the research team.

What will happen to me if I take part?

If you decide to take part, you will be given a consent form to indicate your willingness to participate in the study and agree to the use of your anonymised data. Even if you have decided to take part, you are still free to withdraw at any time without giving a reason.

After expressing your consent, you will take part in the following activities before using the haptic device:

5. A short test of your existing knowledge of cell membranes. You are not expected to know much (if anything) on this subject yet, so don't worry about answering correctly, and it is fine to answer 'unsure' if you need to.
6. A paper based spatial test about Spatial Views and figure turning of 3D objects
7. A fine dexterity test (5 mins) which will involve placing as many metal parts on small pins using fingers and tweezers as you can in 2 minutes.
8. A spatial block design test where you will use your hands to rearrange blocks that have various colour patterns on different sides to match a pattern shown to you.

On a separate day, you will then take part in the learning activity, where you will be video recorded. There will be a short tutorial for you to get used to the equipment. Then, in pairs, you will take turns being the 'pilot' and the 'co-

pilot'. The pilot will wear the oculus rift viewer showing the cell membrane model and use 3D haptic device to manipulate the cell. The co-pilot will be in control of the worksheet instructions and help the pilot achieve the task goals and identify features by being able to view the membrane model on the computer screen.
Once the activity is complete, you will be asked to fill out the online feedback form giving your views on the activity/system and how you found the experience (5 mins). You will also be given the test of cell knowledge again (10 mins). The researcher team will also ask you some questions about your experience (10 mins).

This will be the end of the study. In the event of you wishing to withdraw from the study after submitting your data, you will still be able to do so up to 20/12/17.

<u>What are the possible benefits and risks of taking part?</u>

There are no foreseeable risks in participating in the study. Students will be given the opportunity to use both systems. The study will give you the opportunity to experience new technology which may help students in their learning.

<u>Will my taking part be kept confidential?</u>

The information you provide will be treated with the strictest confidentiality and will be held securely until the research is finished. The data for analysis will be anonymised and your real name will never be used. It will not possible to identify you individually from any reports and papers that are written. There will be no possibility of you as individuals being linked with the data.

The UK Data Protection Act 1998 will apply to all information gathered within the interviews and held on password-locked computers and encrypted hard drives.

<u>What will happen to the results of the study?</u>

The results of this study will be analysed to determine the impact of the haptic system on students' understanding. The results may also be reported through publications in the field of Educational research.

Who should I contact for further information?

If you have any questions or require more information about this study, please contact me using the following contact details:

Researcher name: Megan Tracey
Researcher Email: megan.tracey@kcl.ac.uk

What if I have further questions, or if something goes wrong?

If this study has harmed you in any way or if you wish to make a complaint about the conduct of the study you can contact King's College London using the details below for further advice and information:

Research Supervisor: Dr. Mary Webb
Supervisor email: mary.webb@kcl.ac.uk

Supervisor Address: Dr Mary Webb
School of Education, Communication and Society
Waterloo Bridge Wing
Franklin-Wilkins Building
Waterloo Road
London
SE1 9NH

Thank you for reading this information sheet and for considering taking part in this research.

CONSENT FORM FOR PARTICIPANTS IN RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study:
Using Haptics to Increase Understanding in Cell Biology

King's College Research Ethics Committee Ref:

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Please tick

I confirm that I understand that by ticking/initialling each box I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes mean that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element I may be deemed ineligible for the study. ☐

Please tick

1. I confirm that I have read and understood the information sheet for the above study. I have had the opportunity to consider the information and asked questions which have been answered satisfactorily. ☐
2. I understand that my participation is voluntary, that I am free to withdraw at any time without giving any reason, and that doing so will have no effect on grades or schoolwork. Furthermore, I understand that I will be able to withdraw my data up to 20/12/17. ☐
3. I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998. ☐
4. I understand that my information may be subject to review by responsible individuals from the College for monitoring and audit purposes. ☐
5. I understand that confidentiality and anonymity will be maintained and it will not be possible to identify me in any publications. ☐
6. I agree that the research team may use my data for future research and understand that any such use of identifiable data would be reviewed and approved by a research ethics committee. ☐
7. I understand that the information I have submitted will be published as a report and I wish to receive a copy of it. ☐
8. I consent to being audio/video recorded. ☐
9. I consent that my audio/video may be used at public events, such as academic conferences. ☐

Name of Participant	**Date**	**Signature**
Name of Researcher	**Date**	**Signature**

7.34 Appendix HH: Main Study cell knowledge test

Your understanding of the cell membrane

Cells are surrounded by a membrane called the cell membrane or plasma membrane. This quiz is designed to check what you know about what the cell membrane is like and how it works. Do not worry if you are unsure of the answers. You will be able to learn about cell membranes later.

1) in the spaces below try to write 5 important facts about the cell membrane and try to use as many as you can of the following words: active transport, diffusion, permeable, oxygen, carbon dioxide, glucose, sodium ions, potassium ions, membrane proteins, channel, respiration.

	Fact about the cell membrane	**How sure are you about being correct?**		
1		Very confident	Quite confident	No idea Guessing
2		Very confident	Quite confident	No idea Guessing
3		Very confident	Quite confident	No idea Guessing
4		Very confident	Quite confident	No idea Guessing
5		Very confident	Quite confident	No idea Guessing

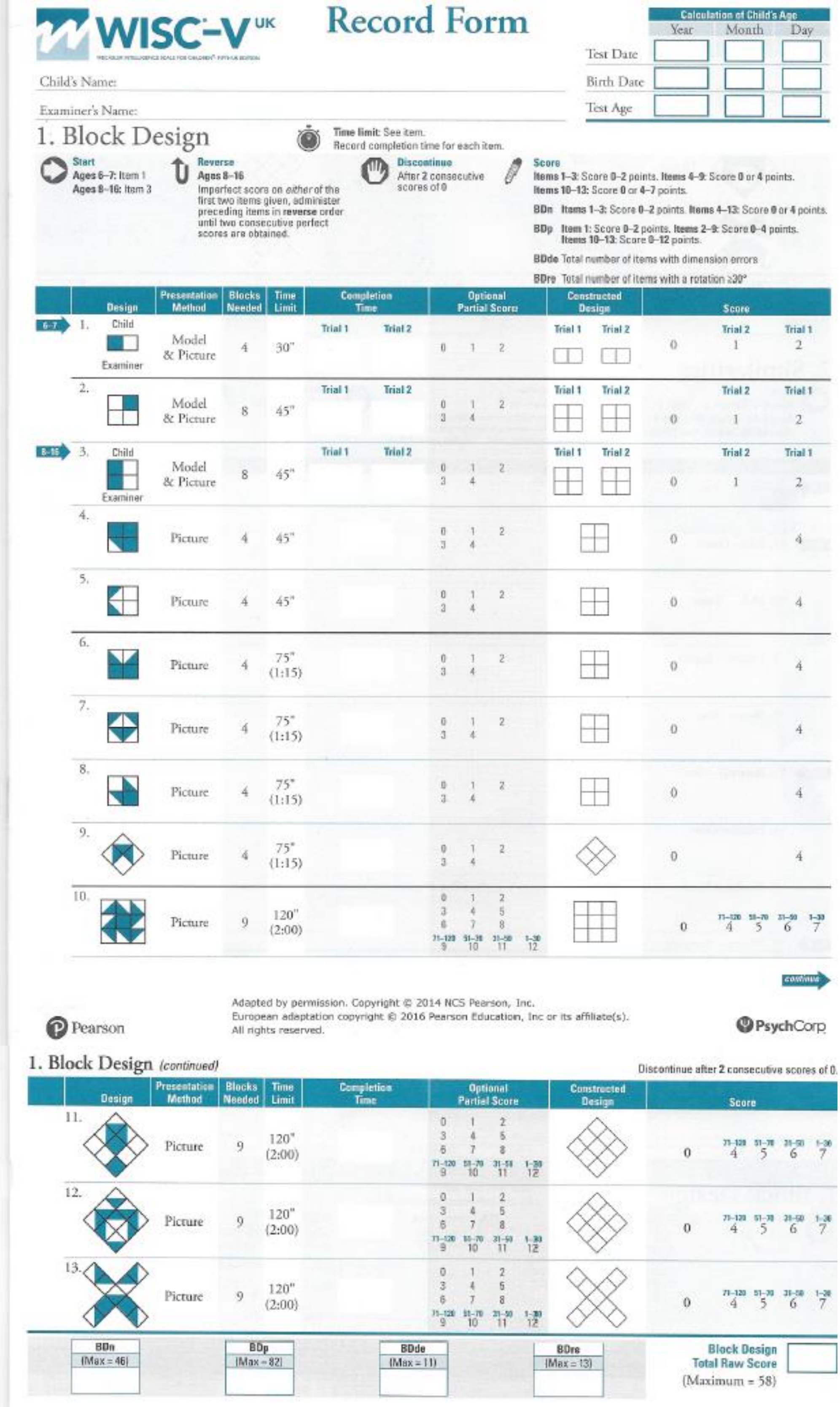
2) Explain why the cell membrane is important for cells in our body

For each of the following statements circle whether you think that the statement is true, false or if you are unsure.

Statement	**True**	**False**	**Unsure**
The cell membrane is a barrier that stops everything from entering /leaving the cell	True	False	Unsure
The cell membrane is fluid	True	False	Unsure
The cell membrane contains membrane proteins that sit in a fixed position in the membrane	True	False	Unsure
All membrane proteins form channels that allow anything to cross the membrane and enter the cell	True	False	Unsure
Oxygen can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Glucose can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Carbon dioxide can freely enter and exit a cell (does not need a channel)	True	False	Unsure
Sodium can freely enter and exit a cell (does not need a channel)	True	False	Unsure
An oxygen molecule is smaller than a glucose molecule	True	False	Unsure

The cell membrane contains about 5 glucose channels	True	False	Unsure
If there is an equal amount of oxygen inside and outside the cell it will be harder for oxygen to enter than if there is more oxygen outside	True	False	Unsure
If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside	True	False	Unsure
During aerobic respiration a cell uses oxygen and glucose	True	False	Unsure
During aerobic respiration a cell produces oxygen and water	True	False	Unsure

7.35 Appendix II: WISC-IV BDT scoring sheet used in the Main Study



WISC-V UK Record Form

Child's Name:

Examiner's Name:

Calculation of Child's Age	Year	Month	Day
Test Date			
Birth Date			
Test Age			

1. Block Design

Time limit: See item. Record completion time for each item.

Start Ages 6–7: Item 1; Ages 8–16: Item 3

Reverse Ages 8–16: Imperfect score on *either* of the first two items given, administer preceding items in **reverse** order until two consecutive perfect scores are obtained.

Discontinue After 2 consecutive scores of 0

Score Items 1–3: Score 0–2 points. Items 4–9: Score 0 or 4 points. Items 10–13: Score 0 or 4–7 points.

BDn Items 1–3: Score 0–2 points. Items 4–13: Score 0 or 4 points.

BDp Item 1: Score 0–2 points. Items 2–9: Score 0–4 points. Items 10–13: Score 0–12 points.

BDde Total number of items with dimension errors

BDre Total number of items with a rotation ≥30°

	Design	Presentation Method	Blocks Needed	Time Limit	Completion Time	Optional Partial Score	Constructed Design	Score
6–7	1. Child / Examiner	Model & Picture	4	30"	Trial 1 / Trial 2	0 1 2	Trial 1 / Trial 2	0; Trial 2: 1; Trial 1: 2
	2.	Model & Picture	8	45"	Trial 1 / Trial 2	0 1 2 3 4	Trial 1 / Trial 2	0; Trial 2: 1; Trial 1: 2
8–16	3. Child / Examiner	Model & Picture	8	45"	Trial 1 / Trial 2	0 1 2 3 4	Trial 1 / Trial 2	0; Trial 2: 1; Trial 1: 2
	4.	Picture	4	45"		0 1 2 3 4		0 4
	5.	Picture	4	45"		0 1 2 3 4		0 4
	6.	Picture	4	75" (1:15)		0 1 2 3 4		0 4
	7.	Picture	4	75" (1:15)		0 1 2 3 4		0 4
	8.	Picture	4	75" (1:15)		0 1 2 3 4		0 4
	9.	Picture	4	75" (1:15)		0 1 2 3 4		0 4
	10.	Picture	9	120" (2:00)		0 1 2 3 4 5 6 7 8; 71–120: 9, 51–70: 10, 31–50: 11, 1–30: 12		0; 71–120: 4, 51–70: 5, 31–50: 6, 1–30: 7

continue

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Pearson PsychCorp

1. Block Design *(continued)*

Discontinue after 2 consecutive scores of 0.

Design	Presentation Method	Blocks Needed	Time Limit	Completion Time	Optional Partial Score	Constructed Design	Score
11.	Picture	9	120" (2:00)		0 1 2 3 4 5 6 7 8; 71–120: 9, 51–70: 10, 31–50: 11, 1–30: 12		0; 71–120: 4, 51–70: 5, 31–50: 6, 1–30: 7
12.	Picture	9	120" (2:00)		0 1 2 3 4 5 6 7 8; 71–120: 9, 51–70: 10, 31–50: 11, 1–30: 12		0; 71–120: 4, 51–70: 5, 31–50: 6, 1–30: 7
13.	Picture	9	120" (2:00)		0 1 2 3 4 5 6 7 8; 71–120: 9, 51–70: 10, 31–50: 11, 1–30: 12		0; 71–120: 4, 51–70: 5, 31–50: 6, 1–30: 7

BDn (Max = 46) | BDp (Max = 82) | BDde (Max = 11) | BDre (Max = 13) | Block Design Total Raw Score (Maximum = 58)

7.36 Appendix JJ: Semi-structured interview questions for the Main Study

Semi- Structured Interview Questions

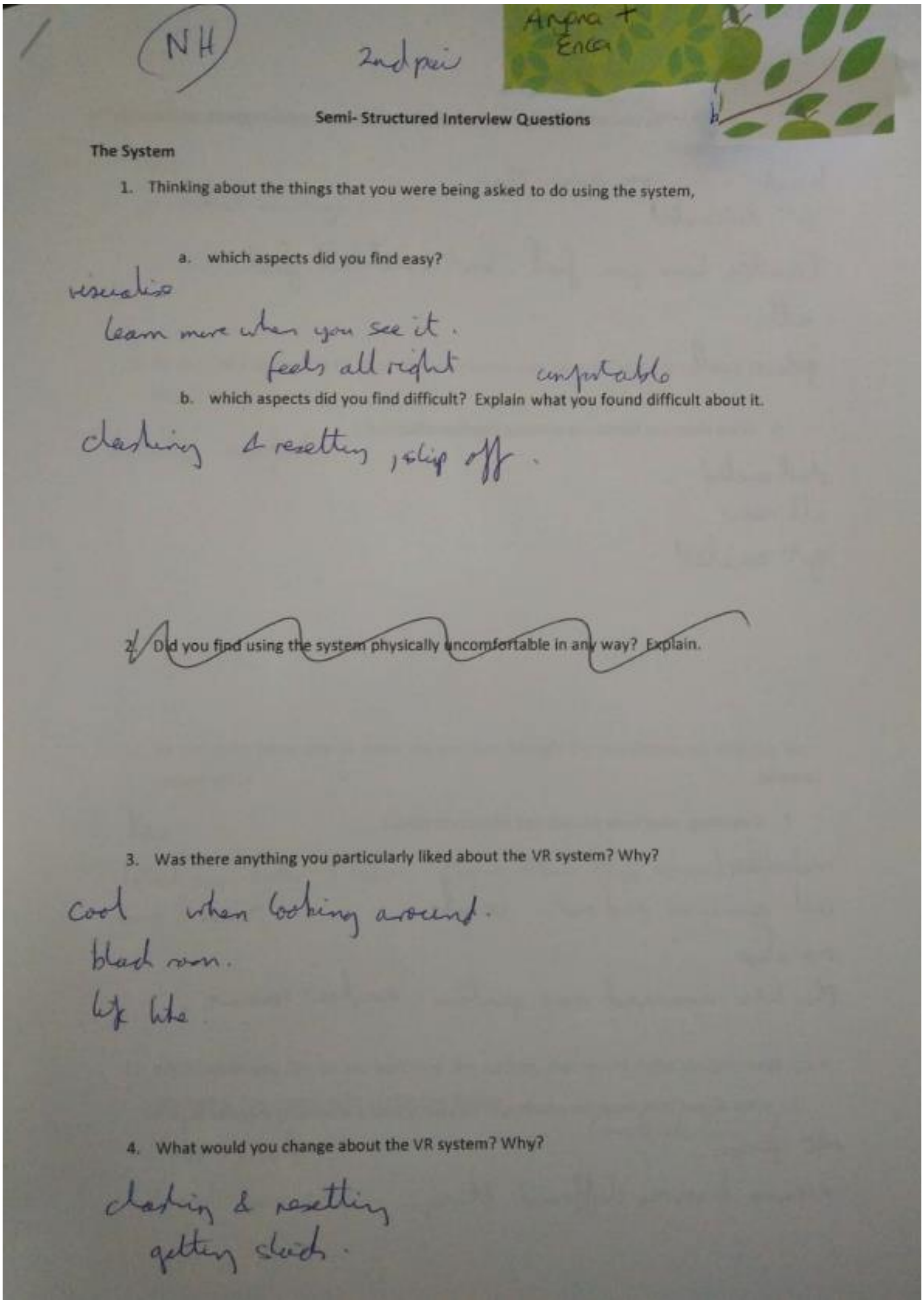
The System

1. Thinking about the things that you were being asked to do using the system,
   a. which aspects did you find easy?
   b. which aspects did you find difficult? Explain what you found difficult about it.
2. Did you find using the system physically uncomfortable in any way? Explain.
3. Was there anything you particularly liked about the VR system? Why?
4. What would you change about the VR system? Why?
5. In this activity, you worked in a pair. How easy was it to work collaboratively whilst using the VR system?
6. Were there any barriers to working together effectively?

Learning

7. If anything, what have you learned about cells today?
8. What do you think were the advantages for your learning of working together in pairs?
9. Did you like learning collaboratively in pairs in this activity?
10. Do you think being able to "feel" the membrane and particles virtually can help you learn better? Why?
11. Do you think being able to move the particles through the membrane can help you learn better? Why?

7.37 Appendix KK: Example of hand-written notes made during the Main Study interviews



NH

2nd pair

Angela + Enca

Semi- Structured Interview Questions

The System

1. Thinking about the things that you were being asked to do using the system,

   a. which aspects did you find easy?

visualise

learn more when you see it.

feels all right comfortable

   b. which aspects did you find difficult? Explain what you found difficult about it.

clashing & resetting, slip off.

2. ~~Did you find using the system physically uncomfortable in any way? Explain.~~

3. Was there anything you particularly liked about the VR system? Why?

cool when looking around.

black room.

life like

4. What would you change about the VR system? Why?

clashing & resetting

getting stuck.

5. In this activity, you worked in a pair. How easy was it to work collaboratively whilst using the VR system?

hard. one person there
get distracted.

Question how you feel but couldn't feel.
all.

got on well.

6. Were there any barriers to working together effectively?

distracted
all new
got excited.

Learning

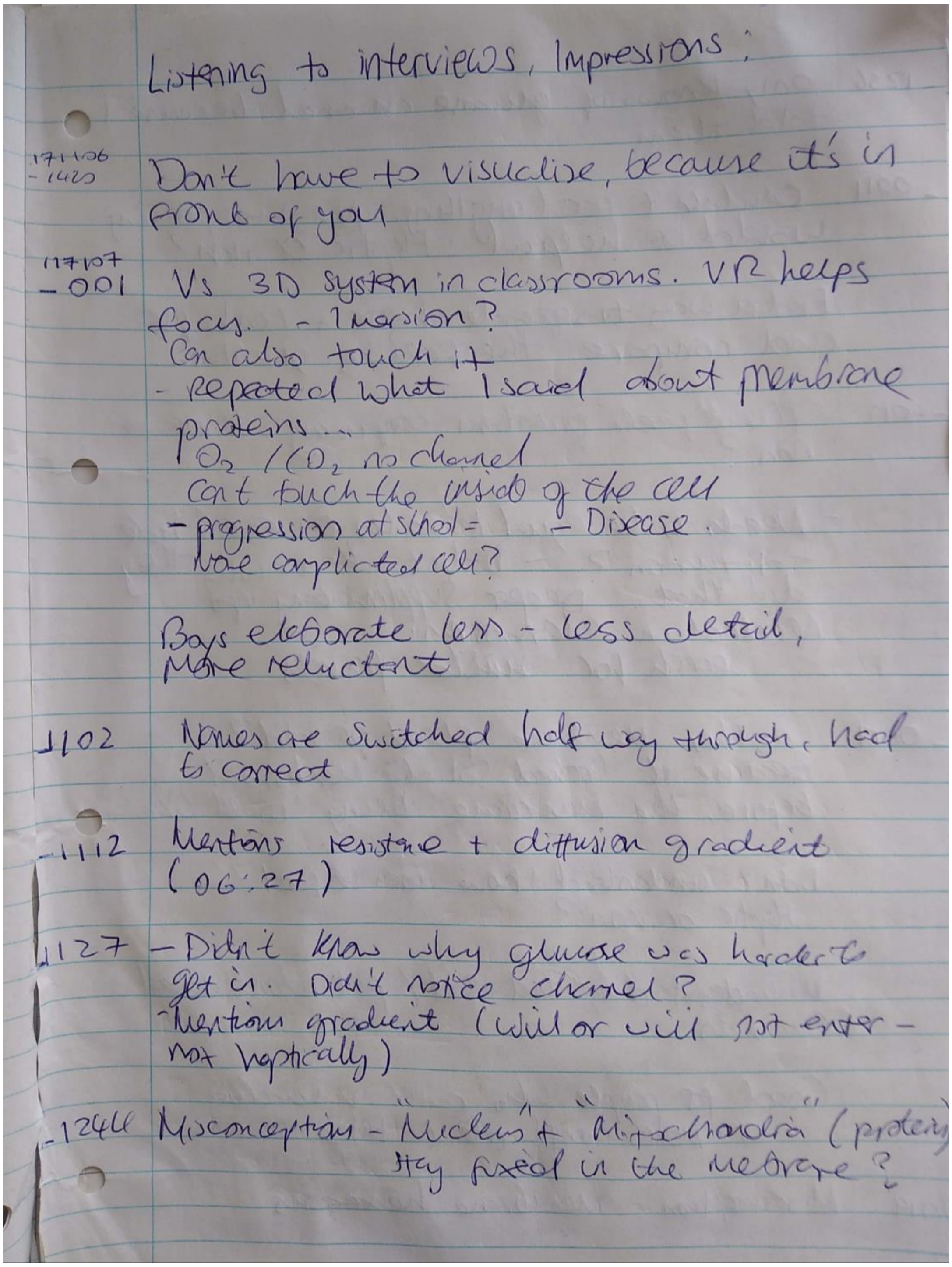
7. If anything, what have you learned about cells today?

movement.
cells going in and out. Labels.
visuals
this time answered more questions. earlier answer.

8. What do you think were the advantages for your learning of working together in pairs?

one person
everyone knows different things.

7.38 Appendix LL: Example of hand-written notes of initial impressions made whilst listening to the interview audio in Phase 1 of the thematic analysis



Listening to interviews, Impressions :

171106 - 1420 Don't have to visualise, because it's in front of you

117107 - 001 Vs 3D system in classrooms. VR helps focus. - Imersion?
Can also touch it
- Repeated what I said about membrane proteins...
O_2 / CO_2 no channel
Can't touch the inside of the cell
- progression at school = - Disease.
More complicated cell?

Boys elaborate less - less detail, more reluctant

1102 Names are switched half way through, had to correct

-1112 Mentions resistance + diffusion gradient (06:27)

1127 - Didn't know why glucose was harder to get in. Didn't notice channel?
- Mentions gradient (will or will not enter - not haptically)

-1244 Misconception - "Nucleus" + "Mitochondria" (proteins) stay fixed in the membrane?

197

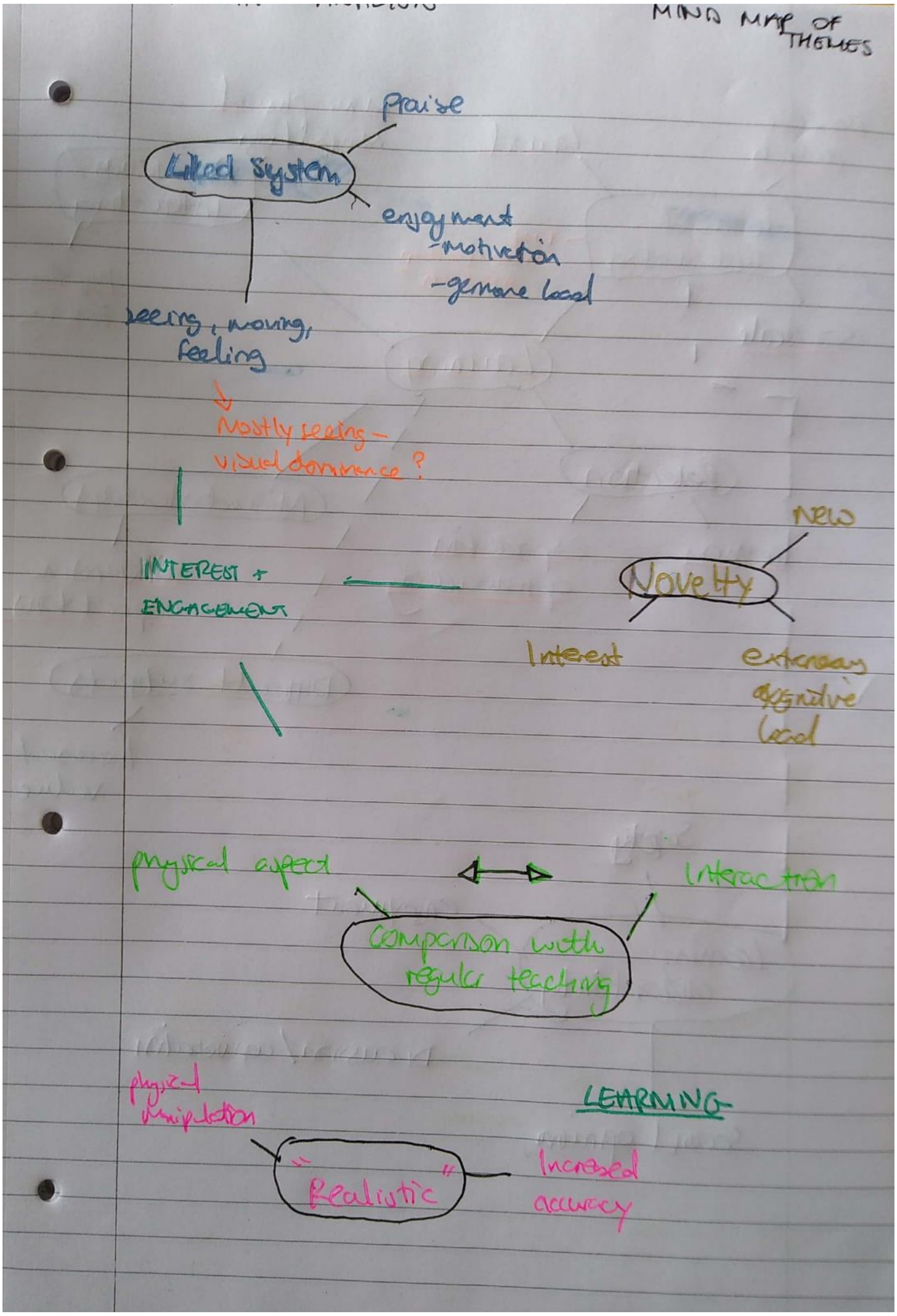
Transcript notes
3

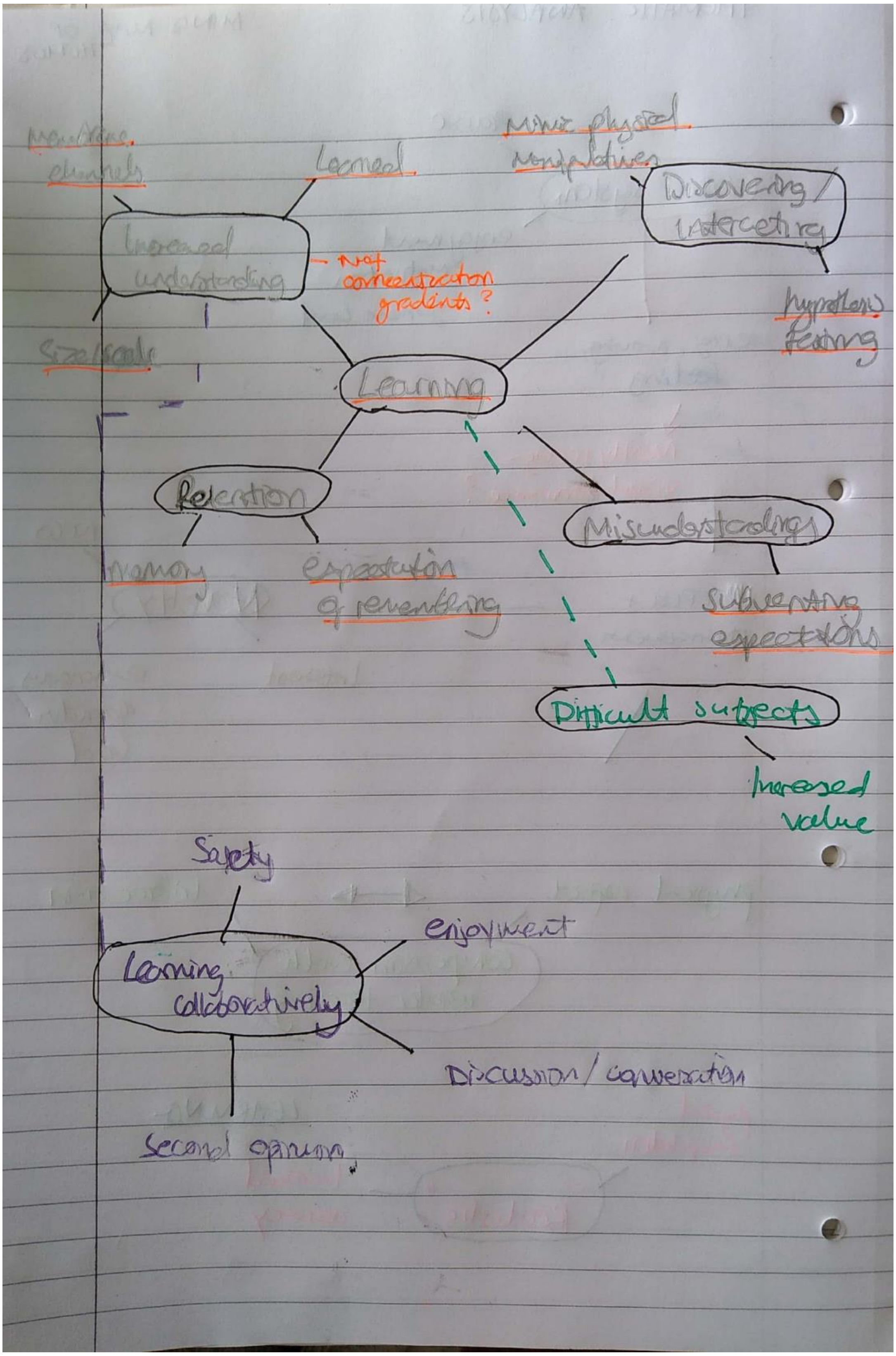
171128-009

- 'seeing things'
- need previous knowledge
- Question worded difficulty
- tech difficulties 'twist in fingers' 'hard to grab'
- 'life like'
- VS powerpoint whiteboard (could actually see)
- labels inconsistent
- ease of communication - difficulties of understanding
- Channels for O_2 + CO_2 (misconception)
- Increased understanding (lack of visualisation in normal teaching)
- Confusion (collaboration) lost
- help understanding (collab)
- Safer (collab) because can't see anything when wearing headset
- fun
- collaboration, discussion, conclusion
- Couldn't feel (non haptic correct)
- Easier to understand when doing it yourself
- Want more feeling (non haptic card)
- Squishy?
- Uncomfortable
- Sound
- different learning styles
- VS powerpoint
- talk, discuss
- fun
- sticks in brain
- New/exciting

- for 'harder stages'
- no notes
- eyes hurt
- overwhelming
- Bouncing

7.39 Appendix MM: Example mind maps used in the identification of themes in Phase 1 of the thematic analysis





Membrane channels
Learned
Mimic physical manipulatives
Discovering / interacting
Increased understanding
not concentration gradients?
Size/scale
Learning
hypothesis testing
Retention
Misunderstandings
memory
expectation of remembering
subverting expectations
Difficult subjects
Increased value
Safety
enjoyment
Learning collaboratively
Discussion / conversation
Second opinion

7.40 Appendix NN: Notes taken on the initial comparison of coding between researchers in Phase 1 of the thematic analysis

Coding Comparison

Table of codes from each user:

Mary Webb (Researcher 2)	**Megan Tracey (Researcher 1)**
Barriers - Distraction (were distracted by the excitement of the system, the nature of the wider space going beyond the activities) *	Additional Sensory input
Comfort (of the interface)	Collaboration - Communication and discussion -Headset as barrier
Cool (or impressed with system)	Division of labour
Correcting (absence of correcting influence)	Remaining grounded and safe
Different view (of pilot and co)	Comparison with regular teaching - Preference for interaction
Difficulties - Dizziness	Great quotes

- Grasping - Instruction needed - Space restriction - technical	
Easy	Haptics - Diffusion
Engagement (system engaging or more engaging than other methods)	Increased understanding
Engagement	Lack of revision potential
Feel resistance	Learning style beliefs
Formulating ideas*	memorability
Great quotes	misunderstanding
Learning - Encourage you to think - Explaining (to each other) - Learn by discovering and interacting with system - Learning collaboratively - Questioning (by each other or just reading and clarifying questions from sheet) - Retention - Understanding (students commenting on their own) - Visualise	movement
Liked features	Novelty

- Feel forces - Feel sensory - Labels - Molecules type and size - Movement of molecules - Moving things - Seeing	
Membrane channels	Praise
Misconceptions	Size and Scale
Negotiating	Task difficulty
Not being able to feel	Using equipment - Labels and identification - Technical difficulties - Uncomfortable equipment
Role of co-pilot - Connection to real-world	Using prior knowledge
Value for difficult concepts	Visualisation and visual words
Vibration	Workspace
Wishes for improvement	

Comparable/overlapping nodes

Megan	Mary
Misunderstandings	Misconceptions
Collaboration	Learning collaboratively
Headset as barrier to communication	Barriers
Division of labour	Role of co-pilot
Remaining grounded and safe	Connection to real-world
Additional sensory input Uncomfortable equipment	Wishes for improvement
Uncomfortable equipment	Comfort
Praise	Cool Engagement Enjoyment
Collaboration	Correcting
Division of labour	Different views of system Role of co-pilot
Workspace Using equipment Technical difficulties Task difficulties Labels and identification Using prior knowledge No revision material	Difficulties - Tech problems - Tech problems - Instructions needed - Labels
Using equipment	Easy
Comparison with regular teaching Preference for interaction	Engagement
Praise	Enjoyment Engagement
Haptics – diffusion	Feel resistance No being able to feel
Communication and discussion	Formulating ideas
Visualising and visual words	visualise
Increased understanding	Learning -understanding
Using Equipment	Easy

	Liked features Difficulties
Memorability	Liked Features Retention memory
Workspace	Difficulties-space restriction Wishes for improvement
Haptics	Vibration
Increased understanding	Membrane channels
Collaboration Role of co-pilot	Correcting
Collaboration Role of co-pilot	Negotiating meaning
Size and scale	Molecules type and size
Labels and identification	Labels
Uncomfortable equipment	Fingers in a twist
Staying grounded	Connection to real world

Notes:

Learning style beliefs has no equivalent.

Value for difficult subjects overlaps with novelty, but I think it does not have an equivalent.

Movement and visualisation/visual words overlap considerably so can be merged?

Great Quotes

Quotes coded as "great quotes", which are especially relevant or interesting and identified for use later on. Matching quotes are colour coded.

Great quotes coded by Mary:

I think as well because you had someone sitting next to you, you could like confirm that you were still sort of in the real world. Because we kept touching each other like, you are still there. Because it's kind of weird.

You're not going to be able to ever go in a cell, because cells are so small, and feel what it's like. But in that you could actually feel what it would feel like, which was really interesting.

it was just like better than watching it on a screen

It was kind of way you could actually interact with it rather than just sitting there and watching the presentation and just like making notes in the book. It was more easy to understand. I found that, anyway. And you could

actually… So like you could actually see that it was harder to move like glucose in and out the cell membrane, rather than just looking at it.
I think as well because you had someone sitting next to you, you could like confirm that you were still sort of in the real world. Because we kept touching each other like, you are still there. Because it's kind of weird.

It's going to be in my head all day, all tomorrow, all, you know, the rest of this week and I'm not going to forget that little wall there and all the molecules moving around.

It was kind of way you could actually interact with it rather than just sitting there and watching

I think because there was like no sound in the background. Like you could like hear each other and work well together by talking to each other.

don't know how to explain it, but there's just… I'd feel a bit lost. Like I could be getting something wrong

don't really have someone there to tell you that you're doing something wrong.

Great quotes coded by Megan:
We all thought it was sort of a barrier and nothing sort of entered and exited but it does lots of things.
Yeah, the glucose was really interesting and the more you had, the more resistance the cell membrane gave. So… Yeah, that was good, I liked feeling that.
I'll never forget what that… It's going to be in my head all day, all tomorrow, all, you know, the rest of this week and I'm not going to forget that little wall there and all the molecules moving around.
It was really good to be able to feel it because it's… You're not going to be able to ever go in a cell, because cells are so small, and feel what it's like. But in that you could actually feel what it would feel like, which was really interesting.

Because it's like 3D because at school you just watch a… You see like a PowerPoint but here you could actually like see it and actually try and like get it and hold it and stuff and move it around.

It was kind of way you could actually interact with it rather than just sitting there and watching the presentation and just like making notes in the book. It was more easy to understand. I found that, anyway. And you could actually… So like you could actually see that it was harder to move like glucose in and out the cell membrane, rather than just looking at it.

I feel like I understood it more by seeing the potassium and all the things… Like moving them around. It was better than watching a presentation on like a white board. Because I feel like I just get bored and distracted, yeah.

It's kind of like your teacher would just say it but you couldn't really understand it. She'd just be like, oh the glucose doesn't really move. But you just wouldn't didn't really know what she meant. What does she mean? It just doesn't really

Because they were easy going from the outside into the inside. Like it could pass them easily because they were flowing. Whereas things like the potassium wouldn't go through as easy. You kind of like you try and push it through but it would just bounce off. You have to actually grab it and put it back on the other side.

Yeah, because it's like someone to talk to you. So if you say something. Because obviously you can't really get everything you… Everything you think, like written down like this to or someone to tell it to like say it to them. And like talk to you about it to see whether you can come to a conclusion about a question or something if you're stuck.

It's easier to understand something when you can actually see it and do it yourself, other than just being told it. So like seeing that you can actually move the oxygen yourself to the other side.

I think it's just because learning is just ***boring,*** *whereas VR is something that's quite new so it's exciting for people*

7.41 Appendix OO: Codebook showing codes agreed upon by both researchers in Phase 1 of the thematic analysis

Thematic analysis initial coding

Nodes-10/05/2018

Name	Description
Comparison with regular teaching	Comments comparing the activity with usual methods of teaching
Preference for interaction	Expression of the preference for interaction compared with other methods of learning (e.g. PowerPoint, watching a presentation/animation, reading from a book, anything that isn't as interactive as this activity). They may express that this increases their engagement or are more willing to learn from this compared to traditional methods.
Difficulties	Difficulties experienced as a result of features of the system. May include technical problems due to malfunction but these have also been identified as a child node
Dizziness	Any mention of dizziness or disorientation from the VR system
Grasping particles	Difficulties with grasping particles
Instructions needed	Comments that students needed instructions or were not sure what to do
Space restriction	Comments about the space restriction within the VR space, e.g. needing more space or getting stuck due to lack of space for movement within the workspace.
Technical problem	Technical problems due to system failure or bugs. Things that were not meant to happen and caused issues using the system.
Uncomfortable equipment	Comments on the physically uncomfortable aspects of the equipment

Name	Description
Fingers in twist	Problems with the way the gimbal moves and allows them to access the space
Easy	Students say they find the system easy or particular things that students said they found easy about using the system
Formulating ideas	Talk about how or whether they were formulating ideas as they discussed
Great quotes	Quotes that might be particularly useful or insightful
Haptics	When words describing the haptic (touch) sense are used, like being able to/not able to feel things.
Diffusion	Comments about being able to feel diffusion. This is the feeling of the diffusion gradient from high concentration to low concentration across the membrane and feeling resistance through the membrane only.
Not able to feel	Comments about not being to feel things through the system.
Vibration	Specific talk about vibration of molecules or particles. These were not always features they liked.
Labels and identification	Comments about the label function and identification of molecules
Lack of revision potential	Comments to do with the lack of material produced from the activity to use for revision. E.g. detailed notes with correct answers.
Learning	Any indications that they believed they were learning. There are a number of child nodes of processes which are usually related with learning
Encourage you to think	Students appeared to feel they were being encouraged to think by the system and the way they were using it
Explaining	Students felt they were explaining to each other
Increased Understanding	Comments about any developments in their understanding or just that they thought they were understanding better

Name	Description
Learn by discovering and interacting with system	Learn by discovering and interacting with system
Learning collaboratively	The broad category of comments about learning collaboratively
Communication and discussion	Comments about communication and discussion whilst collaborating.
Headset as a barrier to communication	Comments framing using the headset as a barrier to communication or the pair's ability to talk or explain to each other.
Remaining grounded and safety as a pair	Comments regarding having a partner in the task to help keep the person using the oculus rift to stay 'grounded' in the real world and safe.
Roles as pilot and co-pilot	Comments about the distinct roles the students had as pilot and co-pilot.
Co-pilot as connection to real-world	Any talk about the co-pilot being a grounding influence on the pilot or a connection to the real world outside of the VR. This is separate to the 'connection to the real world' node as this pertains to the role of the co-pilot as the grounding influence.
Different views of system	Comments about the different views seen by the two students of system as co-pilot and pilot. The pilot is viewing the cell through the VR headset, and the co-pilot is viewing the cell through a monitor, so any discussion about the difference between these two views is coded here.
Questioning	Questioning of students by each other or just reading and clarifying questions from sheet
Retention memory	Talk that suggests students believed that they would remember ideas and facts as a result of using the system
Learning styles beliefs	References to students own or other people's learning styles (e.g. physical or visual) in context of learning from the system or learning in general.

Name	Description
Liked Features	What students like about the system and what they liked about how they used it. They didn't necessarily say that these helped them to learn
feel forces	Specific comments about being able to feel forces as they use the system and liking it. This is often coded in addition to ‘haptics’.
Feel sensory	Comments about liking to feel as they use the system. Not very specific about what they feel. This is often coded in addition to ‘haptics’.
Molecules type and size	Comments about molecules – their type and size. This is usually about what they have learned but not always. I have coded additionally as learning if utterance is specifically about learning
Movement of molecules	Any talk about molecules moving. Sometimes this is about their learning and so it is also coded as learning
Moving things	Utterances about moving things around can include moving particles but this is not always specified. Again, sometimes this is about their learning or supporting their learning but not always
Seeing	Any utterances about how they liked being able to see things in the system
Membrane channels	Any mention of membrane channels
Misunderstanding	Any misunderstandings that were expressed about the workings of the cell are coded here. E.g. Thinking that oxygen and carbon dioxide require channels in the membrane, or that glucose, potassium or sodium do not need channels or flow through the membrane freely.
Need for feedback or confirmation	Commenting on the fact that there is no one to correct you on this task (e.g. a teacher), or that they want someone to tell them whether they are giving the correct answers. Could also be that they are worried that their answers aren't correct.

Name	Description
Negotiating meaning	Dialogue between the pairs where they negotiate the meaning of what they saw and felt
Novelty	Comments on the novelty aspect of the system
Praise for the system	Expressing enjoyment or fun about using the system, or describing it as a good experience explicitly, or using the word cool to express that they are impressed by it.
Engagement	Comments that suggested students were particularly engaged with the system. That this was more engaging compared with the normal lessons. Comments expressing engagement without comparing it to normal teaching can be coded to praise.
Enjoyment	Specific comments about their enjoyment or suggestions that they did enjoy using the system
Task difficulty	Comments about the difficulty of the activity/task. This could be saying that the activity was easy or difficult.
Using Prior knowledge	Comments about having to use, or using prior knowledge in the task, rather than using information solely from the activity.
Value for difficult concepts	Comments about the system or activity being useful for difficult/complicated subjects or concepts.
Visualisation and visual words	Comments about 'seeing the process' or movement in the activity, rather than having to visualise from a diagram, for example. Seeing aspects of the processes across the cell membrane in reference to increasing understanding.
Wishes for improvement	Wishes for improvement – goes beyond just correcting technical problems
Additional sensory input	Expressing opinions that adding sensory input to the system would improve it, whether that be visual, auditory or haptic

Name	Description
Workspace and restriction of space	To do with the workspace available to them, and what they would change about space. This can include asking for a bigger or different space to work in, or anything else. Some of these could be coded as 'difficulties-space restriction' too, but this is for expressed wishes for a change to the workspace.

7.42 Appendix PP: Codebook used in Phase 3 of the thematic analysis after continuous revisions through IRR and negotiated agreement.

Thematic analysis revised coding Phase 3

Nodes:

Name	Description
Comparison with regular teaching	Comments comparing the activity with usual methods of teaching
Preference for interaction/experiencing for themselves	Expression of the preference for interaction compared with other methods of learning (e.g. PowerPoint, watching a presentation/animation, reading from a book, anything that isn't as interactive as this activity). Student may talk about being immersed in the cell biology, getting to experience it themselves, with their own eyes compared to usual. They may express that this increases their engagement or are more willing to learn from this compared to traditional methods.
Concerns for mainstream use	Concerns about bringing the system mainstream.
Lack of revision potential	Comments to do with the lack of material produced from the activity to use for revision. E.g. detailed notes with correct answers.
Difficulties	Difficulties experienced as a result of features of the system. May include technical problems due to malfunction but these have also been identified as a child node
Dizziness	Any mention of dizziness or disorientation from the VR system

Name	Description
Thimble issues	Problems with the way the gimbal moves and allows them to access the space, or any issues with the thimbles including them slipping off fingers
Grasping particles	Difficulties with grasping particles
Space restriction	Comments about the space restriction within the VR space, e.g. needing more space or getting stuck due to lack of space for movement within the workspace.
Task difficulty	Comments about the difficulty of the activity/task. This could be saying that the activity was easy or difficult, or the questions were easy or difficult to answer
Instructions needed	Comments that students needed instructions or were not sure what to do
Technical problem	Technical problems due to system failure or bugs. Things that were not meant to happen and caused issues using the system.
Uncomfortable equipment	Comments on the physically uncomfortable aspects of the equipment
Visual confusion	Not being able to see properly, or not being able to discern what they are looking at
Distraction	Students saying they were distracted from learning by aspects of the system
Easy	Students say they find the system easy or particular things that students said they found easy about using the system
Focus	Comments about being focused on the task or being more focused. May be coupled with comparison to regular teaching if they are describing being more or less focused than usual.
Great quotes	Quotes that might be particularly useful or insightful

Name	Description
Haptics	When words describing the haptic (touch) sense are used, like being able to/not able to feel things.
Concentration gradient	Comments about being able to feel the concentration gradient in diffusion. This is the feeling of the diffusion gradient from high concentration to low concentration or vice versa across the membrane and feeling resistance through the membrane only.
Not able to feel	Comments about not being to feel things through the system.
Vibration	Specific talk about vibration of molecules or particles. These were not always features they liked.
Labels and identification	Comments about the label function and identification of molecules
Learning	Any indications that they believed they were learning. There are a number of child nodes of processes which are usually related with learning
Application of knowledge	Evidence of the student applying what they learned in the system to a wider context
Increased Understanding	Comments about any developments in their understanding or just that they thought they were understanding better
Lack of or problems with learning	Students personally did not feel like they learned anything, or talk about it being hard to learn from
Learn by discovering and interacting with system	Learn by discovering and interacting with system
Membrane channels	Any mention of membrane channels
Molecules type and size	Comments about molecules – their type and size. This is usually about what they have learned but not always. I have coded additionally as learning if utterance is specifically about learning
Questioning	Questioning of students by each other or just reading and clarifying questions from sheet

Name	Description
Retention memory	Talk that suggests students believed that they would remember ideas and facts as a result of using the system
Subverting expectations	Students say that the cell or parts of the cell went against what they expected or what they thought previously.
Learning collaboratively	The broad category of comments about learning collaboratively
Communication and discussion	Comments about communication and discussion whilst collaborating.
Barriers to communication	Comments barriers to communication. This can include anything that makes communication difficult, including the headset or the pair's ability to talk or explain to each other.
Remaining grounded and safety as a pair	Comments regarding having a partner in the task to help keep the person using the Oculus Rift to stay 'grounded' in the real world and safe.
Roles as pilot and co-pilot	Comments about the distinct roles the students had as pilot and co-pilot.
Different views of system	Comments about the different views seen by the two students of system as co-pilot and pilot. The pilot is viewing the cell through the VR headset, and the co-pilot is viewing the cell through a monitor, so any discussion about the difference between these two views is coded here.
Learning styles beliefs	References to students own or other people's learning styles (e.g. physical or visual) in context of learning from the system or learning in general.
Liked Features	What students like about the system and what they liked about how they used it. They didn't necessarily say that these helped them to learn
feel forces	Specific comments about being able to feel forces as they use the system
Feeling in general	Comments about feeling as they use the system. Not very specific about what they feel

Name	Description
Moving things	Utterances about moving things around can include moving particles but this is not always specified. Again, sometimes this is about their learning or supporting their learning but not always
Seeing	Any utterances about how they liked being able to see things in the system
Misunderstanding	Any misunderstandings that were expressed about the workings of the cell are coded here. E.g. Thinking that oxygen and carbon dioxide require channels in the membrane, or that glucose, potassium or sodium do not need channels or flow through the membrane freely.
Need for feedback or confirmation	Commenting on the fact that there is no one to correct you on this task (e.g. a teacher), or that they want someone to tell them whether they are giving the correct answers. Could also be that they are worried that their answers aren't correct.
Novelty	Comments on the novelty aspect of the system
Praise for the system	Expressing enjoyment or fun about using the system, or describing it as a good experience explicitly, or using the word cool to express that they are impressed by it.
Realistic	Students describe the system as realistic or like reality
Using Prior knowledge	Comments about having to use, or using prior knowledge in the task, rather than using information solely from the activity.
Value for difficult concepts	Comments about the system or activity being useful for difficult/complicated subjects or concepts.
Visualisation	Comments about being able to see structure, processes or movement in the activity rather than having to visualise from a diagram, for example. Seeing aspects of the processes across the cell membrane in reference to increasing understanding.

Name	Description
Wishes for improvement	Wishes for improvement – goes beyond just correcting technical problems
Additional sensory input	Expressing opinions that adding sensory input to the system would improve it, whether that be visual, auditory or haptic
Extra learning content	Wishes or suggestions for more learning content in the system. For example, more information on a molecule or the process.
Workspace and restriction of space	To do with the workspace available to them, and what they would change about space. This can include asking for a bigger or different space to work in, or anything else. Some of these could be coded as 'difficulties-space restriction' too, but this is for expressed wishes for a change to the workspace.

7.43 Appendix QQ: Example of the coding log from NVIVO memo feature

8/9/18

Loaded all transcripts

06_1420 coded:

Added focus node after negotiated agreement

Added visual confusion node

Added distraction node

Haptic but no mention of feeling forces. Mentions feeling.

28_0019 coded:

nonhaptic no mention of feeling forces. glucose was harder to move.

molecule type and size moved to learning

mentions channel

Change headset as barrier to communication to just barriers to communication

0017 coded:

subverting expectations node created

nonhaptic, do not talk about feeling, more seeing

0017B coded:

nonhaptic but mentions feeling objects

0015 coded:

nonhaptic -mentions not much to feel

Wants more feeling

0011 coded:

mentions channels

dynamic nature of cell?

feel proteins but nothing else

1306 coded:

channel mentioned

haptic -mentions resistance of particles going through membrane

7.44 Appendix RR: Completion of the worksheet: Number of questions reached/answered for each pair in the Main Study organised by condition

Pair Number	Condition	Question reached out of 15	Questions answered out of 15
5	Haptic	14	14
9	Haptic	13	14
10	Haptic	14	13
11	Haptic	14	13
15	Haptic	12	9
16	haptic	13	12
19	haptic	14	14
20	haptic	14	13
21	haptic	14	14
24	haptic	14	14
28	haptic	14	14
29	haptic	14	14
30	haptic	14	14
33	haptic	14	12
34	haptic	14	14
35	haptic	15	13
14	nonhaptic	14	14
3	nonhaptic	13	12
2	nonhaptic	14	14
1	nonhaptic	15	14
4	nonhaptic	14	14
6	nonhaptic	14	14
7	nonhaptic	14	14
8	nonhaptic	14	14
12	nonhaptic	13	13
13	nonhaptic	14	10
25	nonhaptic	15	15
26	nonhaptic	14	13
27	nonhaptic	14	14
31	nonhaptic	15	9

32	nonhaptic	13	12
36	nonhaptic	13	12
37	nonhaptic	14	11

Average questions reached/answered for the sample overall and by condition:

Condition	Average question reached out of 15	Average number of questions answered out of 15
Haptic	13.8	13.2
Non-haptic	13.9	12.9
All conditions	13.9	13.0

7.45 Appendix SS: Extended version of Table 41: A summary of True/False/Unsure cell knowledge test answers from pre to post-test and results

Statement	Concept	Changes pre to post test	Possible explanation of findings
1: The cell membrane is a barrier that stops everything from entering /leaving the cell	Selective permeability of the membrane	36% answered correctly, and 25% answered incorrectly both pre and post-test. For those who changed their answers, most were from incorrect to correct	Most students did not change their answers. Those who did change mostly changed corrected themselves, but this is a low percentage overall.
2: The cell membrane is fluid	Fluidity of membrane	Majority answered incorrectly in both the pre and post-test (46%).	Misconception was not challenged by the activity. This was expected however, as the fluidity of the membrane was not programmed into the model (Section 3.4.2).
3: The cell membrane contains membrane proteins that sit in a fixed position in the membrane	Membrane proteins and their movement in the fluid cell membrane.	Most answered incorrectly for both the pre-test and the post-test (39%). Second most frequently, participants changed from being unsure pre-test to being incorrect post-test (25%).	Most already held a misconception that proteins are fixed in place. As the second most frequent change was unsure to incorrect, a misconception may have been introduced to those who answered unsure and changed to incorrect.
4: All membrane proteins form channels that allow anything to	Channels/diffusion	Similar numbers of participants in each category	Confusion on this subject. No overall conclusion.

cross the membrane and enter the cell			
5: Oxygen can freely enter and exit a cell (does not need a channel)	Free movement of oxygen across cell membrane.	Most frequently, answers were correct both pre and post-test (46%). Second most frequent change was from unsure to correct (28%). Third most frequent change was incorrect to correct (23%).	Most understood the topic before the intervention. For those who did not, most changed to a correct answer after the intervention.
6: Glucose can freely enter and exit a cell (does not need a channel)	Selective permeability of membrane/glucose transport.	Most frequent unsure pre-test to correct (37%). This was followed by answering correctly in both the pre and post-tests (30%).	Some understanding already, but most of those who did not answer correctly at pre-test showed learning by answering correctly at post-test.
7: Carbon dioxide can freely enter and exit a cell (does not need a channel)	Free movement of CO_2 across cell membrane.	Most frequent answer change unsure to correct (39%). The second most frequent answer change was from incorrect to correct (36%).	Most students demonstrated learning or challenging of misconceptions for this statement.

8: Sodium can freely enter and exit a cell (does not need a channel)	Selective permeability of cell membrane and sodium transport	Similar percentages for several categories	Confusion on the topic
9: An oxygen molecule is smaller than a glucose molecule	Relative sizes of molecules	69% answered correctly pre and post. Next most frequent category was incorrect to correct	Students mostly knew this topic.
10: The cell membrane contains about 5 glucose channels	Nature of the model in relation to the cell membrane.	Most frequent response was unsure both pre and post-test (36%). Second most frequent was unsure to correct (19%). Little variation in frequency between other remaining answer change categories.	This statement was included to see whether students grasped that the model was a small part of the membrane overall. Some students were knowledgeable on this topic before the intervention, and there was evidence of increased learning for some. Little variety in answer change categories past second most frequent indicates confusion on this topic.
11: If there is an equal amount of oxygen inside and outside the cell it will be harder for oxygen	The passive diffusion of oxygen down a	Most frequent category correct both the pre and the post-test (28%), followed by unsure to correct (14%).	A small percentage were able to answer correctly before and after, and evidence of increased learning for some.

to enter than if there is more oxygen outside	concentration gradient	Little variation in frequency between other remaining answer change categories.	Little variation between other answer change categories indicates confusion on this topic.
12: If there is an equal amount of carbon dioxide inside the cell and outside the cell it will be harder for carbon dioxide to leave the cell than if there is more carbon dioxide outside	The passive diffusion of carbon dioxide down a concentration gradient.	Most frequently, students answered unsure at both pre and post-test (20%). Following this was changing from incorrect to correct (18%).	Students more unsure about passive diffusion down a concentration gradient for CO^2 than O^2. It is possible that students were confused by the question resulting in unsure answers pre and post-test. Confusion on this topic suggests that as with O^2, passive diffusion along concentration gradients could be useful in further research.
13: During aerobic respiration a cell uses oxygen and glucose	Aerobic respiration	Majority answered correctly both pre and post-test (64%). The next two most frequent changes were from incorrect to correct (10%) and unsure to correct (9%).	Most already know this fact about respiration. Of those who did not know this fact at pre-test, most changed to a correct answer post-test.
14: During aerobic respiration a cell produces oxygen and water	Aerobic respiration	Most frequently they answered correctly both pre and post-test (45%). Following that, there are few differences between the rest of the answer changes.	Most already know this fact about respiration and retain their confidence in this answer. Little variety in remaining answer change categories indicates confusion on this topic.